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NCRP REPORT No. 88

RADIATION ALARMS AND ACCESS CONTROL SYSTEMS

NCRP

National Council on Radiation Protection and Measurements

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of this and other NCRP Reports see page 70]

NCRP REPORT No. 88

Radiation Alarms and Access Control Systems

Recommendations of the
NATIONAL COUNCIL ON RADIATION
PROTECTION AND MEASUREMENTS

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Preface

This report is part of a series prepared under the auspices of Scientific Committee 46, Operational Radiation Safety. Two fundamental aspects of radiation safety are control of access to areas where unacceptable levels of radiation exposure may exist and provisions for alarm systems to alert personnel when potentially hazardous radiation levels are present. This report addresses both of these aspects and provides guidance from which professional radiation safety personnel can tailor a system to meet the needs for any particular operation or facility. It does not include systems to protect the public or the environment outside a facility nor does it include regulatory requirements for nuclear power plants.

Two reports have already been published as part of this series: NCRP Report No. 59-Operational Radiation Safety Program and NCRP Report No. 71-Operational Radiation Safety-Training. Under preparation at this time are reports treating radiation safety in the mineral extraction industry, dose reduction for occupationally exposed medical and allied health personnel, survey instrument calibration, radiation protection records, radiation protection for medical and allied health personnel, emergency planning and radiation protection design guidelines for particle accelerator facilities.

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Bethesda, Maryland
2 September 1986

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1. Introduction

1.1 Purpose

In facilities where radioactive materials are handled, or where radiation-producing equipment is used, the building, the equipment, and the associated safety procedures should be designed and developed together to provide a safe work environment. The specific combination of requirements for a given facility is defined by the operational radiation safety program.

The specific elements to consider when establishing a new facility are outlined in National Council on Radiation Protection and Measurements (NCRP) Report No. 59, "Operational Radiation Safety Program" (NCRP, 1978a). Two of the elements of an operational radiation safety program are radiation alarm and access control systems. (In NCRP Report No. 59, Section 4, these are referred to as warning and security systems.) The purpose of this report is to provide a more detailed discussion of radiation alarm and access control systems than could be provided in NCRP Report No. 59.

It should be emphasized that this report describes a range of alarm and access control systems that can and do provide an acceptable level of safety at many types of facilities. Depending on circumstances, the solutions offered here may not be appropriate for certain facilities because they are too restrictive, not restrictive enough, or do not cover all circumstances. Thus, this document is offered as a starting point providing ideas that professional health physicists can adapt to meet the needs of a particular situation. Under no circumstances should this report be interpreted in "cookbook" fashion, with literal adherence to every recommendation demanded, nor should it be expected to provide adequate protection in every case without consideration of local conditions.

It is also worth noting that the weakest link in any system of personnel protection is not the hardware but the people themselves. The single leading cause of accidents is the failure of personnel to follow established procedures. Thus, the simplification of procedures, regular training, and replacement of administrative control with hardware that does not unduly impede the normal operation of the facility will go a long way toward reducing the potential for accidents.

1.2 Definitions

1.2.1 *Alarm System*

The proper design of a building and its equipment, and the implementation of appropriate safety procedures, can reduce the likelihood of unnecessary occupational radiation exposures. However, the possibility that such exposures will occur can never be eliminated completely. Facility and equipment failures or procedural errors or oversights may result in the degradation of a safe working environment. *In this report, a system that provides instruction, alerts individuals to a potential or actual change in the safe working environment, and that may initiate mitigating actions is defined as a radiation alarm system.*

A radiation alarm, either visual or audible, may result from an increase in the radiation exposure rate or an increase in the amount of ambient airborne radioactive material. Also, the alarm system may initiate some action such as shutting off the high voltage to an accelerator or x-ray machine, returning a radiation source to its shielding enclosure, or activating an air scrubber system.

1.2.2 *Access Control System*

In many facilities where radioactive materials are handled or radiation-producing devices are used, there are areas where high dose rates or high concentrations of airborne radioactive material may be present during normal operations. *If there is potential access to these high levels of radiation or airborne radioactive material, a system must be provided to reduce the likelihood of unauthorized or inadvertent access to these areas or to the hazard itself. In this report, such a system is defined as an access control system.*

Components in an access control system can include signs, lights, audible signals, physical barriers, interlocks, run/safe switches, pre-start-up notification procedures, instruction, emergency shutdown switches, and administrative procedures.

1.3 Scope

This report discusses the considerations involved in the proper selection, design, and operation of both alarm and access control systems. The purpose of these systems is to minimize inadvertent, but potentially significant, radiation exposures to personnel, including employees, visitors, or contractors within a given facility. Systems designed to protect the general public or the environment outside a facility are not treated. A facility can be a portion of a building, a whole building, or a group of buildings and surrounding environs located at a particular geographical site. This report does not specifically address alarm or access control systems for nuclear power plants, which are subject to specific Nuclear Regulatory Commission (NRC) regulations.

This report also includes a discussion of protective function logic systems which are an integral component of many access-control and alarm systems. Protective function logic circuits provide an interface between the input signals from radiation detectors, interlocks, or other sensors to activate warning devices and/or initiate actions to reduce hazardous levels of radiation.

The treatment of radiation alarm and access control systems discussed in this report will be limited to fixed installation systems. Such systems may be installed on a permanent or a temporary basis (see Section 2.1). This includes equipment such as continuous air monitors (CAMs), radiation area monitors (RAMs), interlock systems, and warning lights, but not portable devices such as survey meters, pocket chirpers, or pocket dosimeters. Also not included are devices such as hand and foot counters and portal monitors, which are designed primarily to monitor individuals rather than the work environment.

1.4 General Considerations

The specific selection of components, installation configuration, and degree of sophistication of a radiation alarm or access control system is determined by the magnitude of the potential radiation hazard and the likelihood of inadvertent exposure. For example, in the case of an access control system, if the radiation hazard is relatively minor, *e.g.*, a calibration facility where a small radioactive source is exposed, then a simple warning sign and a rope barrier might be sufficient. However, if trying to prevent access to an accelerator target cave that may contain immediately life-threatening levels of radiation, then an elaborate access control system including interlocks, warning lights, and signs would be required.

Both access control systems and alarm systems are designed to provide warning to facility occupants. The former are designed to keep facility personnel out of hazardous work environments, and the latter are designed to alert facility personnel should their work environment become hazardous. In this sense, both types are radiation warning systems. The basic components of radiation warning systems, as discussed in this report, are shown in Figure 1.1

Although the scope of this report is limited to fixed installation systems, portable radiation monitoring devices and personnel monitoring equipment are often used for radiation alarm and access control purposes. Typical applications would be the use of pocket chirpers and portable survey meters by a person entering the accelerator target room after shutdown, or the use of a hand and foot counter in a radioactive materials handling laboratory. Portable radiation monitoring devices and personnel monitoring equipment should be considered for use in conjunction with fixed installation equipment when developing a comprehensive radiation alarm and access control system for a facility.

The possibility exists that a radiation access control or alarm system will give a false warning, but any warning information provided by these systems should be heeded until it is confirmed to be false. The number of false alarms should be kept to an absolute minimum, since they tend to cause people to lose confidence in the system and perhaps to ignore the warning. Portable survey meters and personal alarming dosimeters, although not included in this report, are often used to confirm the accuracy of this warning information.

There are many national, state, and local agencies that have regulatory authority over the use of radiation-producing equipment and radioactive materials. Such agencies include the Nuclear Regulatory Commission, the Occupational Safety and Health Administration, the Food and Drug Administration, the Department of Energy, many state health departments, and in some cases, local agencies. Whether one or more of these agencies has regulations or guidelines for radiation alarm and access control systems that apply in a specific case depends on the type of facility.

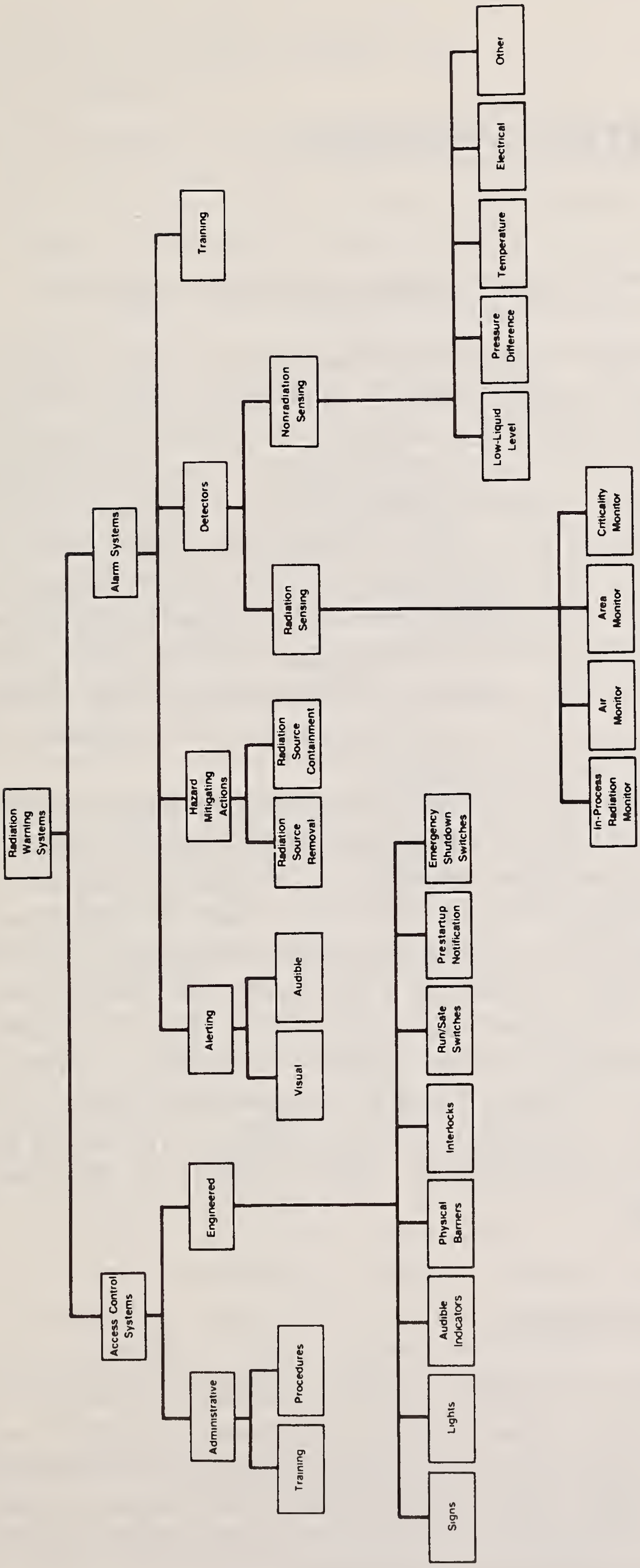

Fig. 1.1. Radiation Warning Systems.

2. Alarm Systems

2.1 General Description and Criteria

Radiation alarm systems are those that provide an audible and/or visual warning of the presence of a radiological hazard. These systems include various sensing devices that give rise to an alarm if a preset level is exceeded or a potentially hazardous situation is detected. The sensing systems may detect radiation fields or radioactivity concentrations of concern or may monitor any one or several of a number of variables such as time, liquid level, or operation of pumps, blowers, or similar systems whose malfunction may result in an immediate or potential radiological hazard. Thus, the alarm system may be direct in that it detects the presence of the radiation field, or indirect, in that it infers the actual or potential presence of a radiation field from measurement of other parameters.

Alarm systems may be either permanent or temporary installations. Temporary installations are usually transportable systems, and frequently serve to augment or substitute for existing permanent installations for a limited time. They may be used in situations where a radiological operation such as industrial radiography is performed on a temporary basis, or in lieu of a permanent installation that may be temporarily nonfunctional. Such systems have all of the characteristics common to permanent alarm systems. Permanent installations are those which are an integral part of the operation that may produce a radiation hazard. In general, such installations are fixed or hardwired in place and operate without need for action on the part of the operations staff.

2.1.1 *Types of Systems*

2.1.1.1 *Radiation Sensing Systems.* Radiation sensing systems are those in which the radiation field is monitored directly by an appropriate detector that, in turn, activates a warning device when a preset radiological condition has been reached. Such systems include:

a. remote or radiation area monitors (RAMs), which are also known as area radiation monitors (ARMs),

b. criticality accident alarm systems,
c. continuous air monitors (CAMs), and
d. effluent monitors.

Detailed descriptions of these systems are available in publications (LBL, 1983; NSAC, 1981) and in manufacturers' literature.

In general, radiation sensing systems are preferable to indirect systems because the warning provided is initiated by actual measurements of radiological conditions in the area or location of concern. RAM systems are thus used to monitor ambient radiation levels within a room or other open location and activate an alarm when a predetermined level has been reached or exceeded. Most commonly, RAM systems measure radiation exposure rate, but some systems have been devised that will trigger the alarm after accumulation of a specified time-integrated radiation exposure. RAM systems are generally useful only for ionizing radiations with relatively high penetrating ability, such as x rays and gamma photons or neutrons. With suitable detector design and calibration, RAMs can be used for detecting beta radiation or electrons with kinetic energies greater than a few hundred keV, and as beam monitors for detection of high-energy heavy charged particles.

Criticality accident alarm systems, sometimes referred to as criticality monitors, are a special class of RAMs with the explicit function of detecting the release of ionizing radiation from an unplanned or accidental nuclear excursion or criticality. Such devices must, of necessity, respond to pulses or bursts of high intensity radiation. Guidelines for criticality monitors have been provided by the American National Standards Institute (ANSI, 1979a). A criticality accident alarm system may detect either the prompt neutron or the gamma radiation associated with the divergent neutron chain reaction. These systems may activate the alarm in response to change in the intensity of the radiation field (*i.e.*, a rate-of-rise system) or to a predetermined level of intensity. Criticality accident alarm systems may also serve the dual function of providing general area radiation monitoring.

Most criticality alarm systems require that at least two detectors respond in coincidence above an existing radiation level in order to trigger an evacuation signal. The purpose of this requirement is to reduce the possibility of false alarms should only one detector be exposed to an elevated radiation field or malfunction with an upscale reading.

CAMs are area monitors that sample the ambient air and evaluate it for gaseous or particulate radioactive material content. When monitoring for gaseous radioactivity, the air may first be filtered to remove the particulate radioactivity and thus avoid interference from this source. Gaseous radioactive material—for example, tritium—is commonly measured by means of a "flow-through" detector, in which air is drawn continuously through an ionization chamber at a constant known volume rate. The amount of ionization produced in the chamber by radiation from radioactive decay is a function of the type and concentration of gaseous radioactive material in the air. Gaseous radioactive material can also be measured with other devices such as Geiger-Mueller or scintillation detectors mounted outside of a pipe or duct through which the radioactive material is flowing.

If the radioactivity concentration is to be measured by means of flow-through or similar detectors, the response of these detectors to external radiation fields must be minimized. Such devices are of limited value in areas where ambient penetrating photon intensities are variable or relatively high. Some protection against external radiation sources can be achieved by appropriate shielding of the detector or by the use of dual detectors and compensating circuitry that subtracts the signal attributable to the external field (see also 2.2.1.4).

The most common continuous air monitors are those that draw a sample of air through a filter on which radioactive particulates are deposited. The radioactive material on the filter is then counted by a conventional detector, commonly a thin window Geiger-Mueller counter, a scintillation detector, or a solid-state detector. Both fixed-filter and moving-filter devices can be used for radioactive particulates. The former continuously collects on a single filter a sample that is evaluated by a detector. The detector provides a signal to a rate measurement device programmed to alarm at a preset level (*i.e.*, when a specific counting rate is exceeded or when a preset rate of rise in the counting rate is exceeded). Because of the simpler circuitry required and the greater versatility of the instrument system, alarm activation is most commonly accomplished by instruments that provide a signal when a given counting rate has been exceeded. To avoid interferences from naturally occurring radon decay products, the filter can be evaluated directly by a single-channel analyzer, with upper and lower energy window discriminator settings appropriately set to bracket the energy of a specific gamma photon emitted by the radionuclide of interest. Spectrometry techniques are also commonly used for monitoring plutonium and other alpha emitters. Alternatively, a moving filter system can be used to minimize the effects of accumulating background radioactive material (see also 2.2.1.4).

Monitors are used for both liquid and gaseous effluents, and they frequently have process control functions in addition to providing warning of elevated radioactivity levels. Gaseous effluent monitors are most commonly CAMs equipped with Geiger-Mueller detectors, although scintillation and other similar detectors have been used to detect the radiation associated with the effluent stream. Liquid effluent monitors include the general class of instruments known as fission product water monitors. With these, an appropriately protected detector can be immersed in the liquid stream, or a detector external to the stream can be used, with the reading correlated with the measured radionuclide concentration in the liquid.

2.1.1.2 *Nonradiation Sensors.* Activation of radiation warning alarms through direct measurement or detection of the hazardous or potentially hazardous radiation field is generally the preferred technique. However, there may be situations in which indirect measurements are preferable. Various non-radiological parameters can provide presumptive indication of an existing or potential radiological hazard and may be used to initiate warning signals. Use of indirect detection methods is often based on practicality, where direct measurement of radiation may be difficult or virtually impossible or may not provide the desired margin of safety or reliability. For example, direct measurement of pulsed sources may not only be difficult to accomplish, but also the activation of a warning based on detection of the pulse may not provide the warning until after the radiological field has disappeared and the hazard no longer exists. In such cases, prudence may dictate advance warning based on the imminence of the pulse such as the accumulation of charge on a capacitor or the activation of the high-voltage generator.

Indirect measurements are often used with radiation-generating devices such as x-ray machines and particle accelerators. In such devices, the radiation warning signal may be activated by the presence of a potential across the primary side of the high-voltage transformer. The warning is thus activated whether or not the current is flowing and radiation is being produced, and it therefore only suggests, rather than being absolute evidence of, the presence of a radiation field. Alternatively, although with somewhat greater technical difficulty, the current flow through or potential across the generating tube can be detected and used to activate a warning system. While this is more positive, inasmuch as radiation will not be produced without a current flow, it again is an indirect measurement of a potential radiation field.

For the x-ray example cited, indirect measurement may be justified for several reasons. Direct measurement of the radiation field produced by the device may not be readily accomplished; for example, with x-ray diffraction units, the x-ray beam, although of very high intensity, is generally of low energy and small cross-section. Appropriate quantitative detectors may be difficult or expensive to acquire, and their installation may interfere with the operation of the apparatus. In some cases, this may even result in an increased exposure potential due to leakage or scattering.

Temperature, water level, air flow, pressure, position, and similar physical quantities can also be monitored and used to activate a radiation warning alarm. For example, where water is used to provide shielding over a radioactive source, the depth of water determines the intensity of the radiation field overhead; hence, a water level indicator, suitably calibrated, could be used to activate a warning alarm when the water level drops to a pre-established depth. Similarly, source position indicators are commonly used in source transfer systems and radiographic applications in which the source is moved from a shielded position to an unshielded one. Activation of the warning or alarm system is presumptive evidence of a radiological hazard; the presence of the radiation field should be verified by direct measurement.

2.1.2 *Alarm Devices*

Alarm systems normally have local alarm devices in the areas occupied by operating personnel to alert them to changing conditions and abnormal levels of radiation. They may also have remote alarm devices in a facility control room, *e.g.*, for a nuclear reactor, accelerator, gamma irradiator, fuel processing facility, or fuel reprocessing facility; or in a central area under the observation of facility administration or radiation safety personnel, *e.g.*, a sealed source manufacturing facility (ISA, 1979).

To minimize failure of radiation alarm and access control systems, fail-safe design and components should be used (see Section 5.1 for a discussion of fail-safe). However, it is obviously not possible to make components or systems completely fail-safe. Therefore, depending on the potential levels of radiation or radioactivity concentration that individuals may be exposed to in case of failure, it may be desirable to guard against the most common failures by installing a system that will detect them and activate appropriate warning devices (Hartin and Goodman, 1971).

The decision to select an audible or visual alarm device, or a combination of the two should be based on the criterion of maximizing the probability that the warning is observed. For example, an audible alarm may not be readily detected in an area of high background noise, and a visual alarm may not be noticed in an area with visual obstructions.

Frequently, personnel are warned of an abnormal condition by radiation detectors simultaneously activating both a visual signal device and an audible signal device. An example of this would be a control room console annunciator panel that provides both visual and audible signals.

2.1.2.1 *Visual Signal Devices.* Visual signal devices usually are illuminated when activated. Different colors, provided by colored bulbs or lenses, can be used to differentiate between hazard types or levels. Depending on the specific use, the light may be steady, flashing off and on, or a rotating beacon. Installing lights in pairs should be considered so that it will be obvious if one of them burns out. Illuminated instructional signs that advise personnel of potentially hazardous conditions are included in this category. Also, room lighting is often dimmed or cycled to warn personnel in the room that irradiation is about to begin.

The configuration, size, intensity, and location of a local alarm light should be such that it is easily observable by all personnel occupying the work area being monitored. Depending on the size of the work area, a system consisting of several alarm lights activated by the same radiation sensing equipment may be required to alert all personnel. Frequently, a flashing light or a rotating beacon light may be used to gain the attention of personnel.

The possibility of color blindness should be considered to ensure that affected personnel understand the meaning of the alarm whenever it is activated. This can be accomplished by permanently installing adjacent to the alarm light a simply-worded, readily-visible instructional sign that defines the purpose of the alarm, or by supplementing the alarm light with an audible alarm. For alerting a visually-impaired person, an audible alarm, a tactile device acting through the sense of touch, or procedures established to ensure the presence of a sighted person in the work area whenever a visually-impaired person is present should be considered.

On some radiation devices, the visual signal device may be a mechanical indicator, *e.g.*, a source-position-indicating rod on a cobalt-60 medical teletherapy unit, or a shutter position indicating arm on an industrial gauging unit (ANSI, 1979b).

2.1.2.2 *Audible Signal Devices.* Audible signal devices include bells, buzzers, horns, sirens, or public address system speakers. Prerecorded messages can be used to alert personnel to impending radiation danger, and a tone alert can be broadcast. Like visual signal devices, audible signal devices can be used both locally and remotely. More than one type of audible signal device can be used to differentiate among hazard types or levels. Each audible signal device should provide a signal distinctive from other audible devices to avoid confusion about the meaning of a signal, and each should be loud enough to be heard above ambient noise levels. The thoroughness of the training program for audible signal devices should be commensurate with the complexity of the system.

Audible signals may be continuous or intermittent. In the case of a siren or an electronically produced sound signal, the frequency may be cyclically altered to produce a distinguishing sound. Detailed guidance on immediate evacuation signals can be found in an American National Standard (ANSI, 1979d).

Consideration should be given to hearing-impaired personnel. Means other than audible signal devices should be used to alert them to an alarm condition, such as use of an alarm light or of a tactile device, or procedures established to ensure the presence of a non-hearing-impaired person in the work area whenever a hearing-impaired person is there.

2.1.3 *Alarm-Sensor Interface*

When the radiation sensor is physically separated from the alarm device by a long length of electrical cable, particular care should be paid to the sensitivity of the system to spurious signals that could result in false alarms or in the converse situation, a failure of the system to respond properly. Protecting the cable from spurious signals may require the use of shielded cable, metal electrical conduit, metal raceways, or cable trays. Care must be taken in the design and installation of alarm systems to ensure that impedance matches are maintained and that loss of signal over long lines is not excessive. Protection may also be required from physical damage, deliberate or inadvertent tampering, and environmental effects (see Section 2.2.1.3).

2.2 Functional Considerations

2.2.1 *General System*

To be effective, a warning system needs appropriate capabilities, including the ability to respond under accident conditions. General criteria and guidance specific to radiation alarm and access control systems are available (Selby *et al.*, 1972; ANSI, 1975; 1978; 1979a; Bramson *et al.*, 1976; Powell, 1980).

2.2.1.1 *Power Requirements.* The power requirements of the instrument system should be met by conventional and readily obtainable sources. Installed systems are usually powered directly from the power outlets, which in the United States provide nominal alternating current voltages of 115-120 V or 230 V, single phase. However, it should be noted that there is not a precise power outlet voltage standard, and considerable variation may occur from locale to locale, as well as with time, at any given location, depending on the system load. A variation in power outlet voltage of ±10 V over a period of 24 h is not extraordinary in some locations. The 60 Hz is usually constant to within ±1 Hz, and normally varies by less than 0.2 Hz during any 24-hour period.

The installed system should thus be capable of operation over an appropriate range of supply voltage, and it should not be damaged or otherwise rendered inoperative by normal voltage swings. Neither should voltage changes over the range normally encountered result in false alarms or excessive maintenance requirements. Protection may be required against voltage surges or transients, which may result in false alarms and may also damage detectors or other voltage-sensitive components. Voltage regulators or line isolation are typically used to achieve protection against line voltage changes.

Loss or restoration of power to the system should not result in activation of the alarm signal. Emergency power supplies are desirable to assure operation in the event of loss of power to the outlet; the greater the potential hazard, the more important the necessity for a back-up power supply. In general, back-up power supplies are essential for alarm systems warning of life-threatening situations that may occur even with the loss of power, such as in facilities that have large radioactive sources or large quantities of radioactive material. Emergency power is not usually required for alarm systems for radiation-producing machines inasmuch as they cease to be a hazard with the loss of power.

Switching from primary to back-up power supply should be automatic and instantaneous and should not introduce spurious signals or false alarms into the system. An indication that a power failure has occurred should be provided. There should be no degradation of system operation while on back-up or auxiliary power.

Instruments powered by direct current should use readily available batteries in accordance with recognized standards (ANSI, 1972a). When batteries are used for emergency or back-up power, it is desirable that they be given a constant trickle charge by connection to the mains. This minimizes the possibility of battery failure. Battery powered instruments should be designed so that a positive indication is provided in the event of battery failure or whenever the battery output falls below a minimum acceptable value; indicator lights and audible signals have both been successfully incorporated into various instruments for this purpose.

2.2.1.2 *Response Time.* A key feature of any alarm system is the time required to initiate the alarm once the preset alarm level has been reached. For systems used to warn of very high or extreme radiation doses (see Section 6.1) such as in criticality incidents, a response time not to exceed one-half second has been specified in various standards and is commonly accepted as being well within present capabilities (ANSI, 1981; Bramson *et al.*, 1976). Also, consideration should be given to the time required for individuals or equipment to take mitigating action once the alarm has been initiated. (A discussion of possible mitigating actions can be found in Section 4.)

2.2.1.3 *Environmental.* Instrument selection and use should take into account the environment in which the instrument may operate. Numerous environmental factors, either singly or in combination, may prevent the instrument from activating an alarm or may trigger a false alarm when a limiting condition has been exceeded. Environmental factors to be considered include the following:

a. unwanted ionizing radiations,
b. microwave, radiofrequency, and other nonionizing radiations and fields,
c. temperature,
d. moisture,
e. ambient pressure,
f. corrosive atmospheres,
g. acoustical pressure,
h. vibration,
i. shock,
j. dirt, dust,
k. mechanical damage by pests.

The first two items listed above constitute interfering radiations which are discussed in Section 2.2.1.4.

The alarm system should be capable of operation over the range of temperatures, humidities, and ambient pressures to which it will be subjected during normal and emergency (*i.e.*, accident) conditions. Temperature changes can induce subtle effects that may render an alarm system inoperative or alter the sensitivity of the sensor or associated electronics. Long-term exposure to high temperatures well within the assumed operating range of the instrument can result in component failure due to accelerated aging, which, if undetected, may render the system inoperative. Temperature extremes beyond the design range of the instrument may also result in prompt failure of components; such failures may be temporary, with recovery occurring when the temperature of the failed component(s) returns to the operational range. Temperature-induced failures may be intermittent and nonreproducible, and hence difficult to diagnose and rectify.

Excessive temperatures may be produced in sensitive alarm systems by self-generated heat. Heat is a by-product of the operation of electronic equipment and must be dissipated with appropriate means. Cooling vents are the simplest and most economical method of providing for heat removal, but air movement by convection may be inadequate and may require augmentation by fans or other air movement devices. Vents also have the disadvantages of providing openings through which dust or damaging corrosives may enter the apparatus, or of being blocked by nearby objects. Fins and other radiative cooling devices may also be used, and may permit the unit to be sealed to protect against dust, humidity, and other corrosives. Components of the system should be placed so that there is adequate removal of self-generated heat.

Either excessively low or high relative humidities may damage alarms or associated system components. High relative humidity may oxidize various metallic components or may damage sensitive electronic or other parts. In extreme situations, humidity may result in condensation and resultant electrical leakage, particularly if temperatures fall below the dew point. Although the range of indoor humidities is normally not excessive, seasonal extremes do occur. For example, during the winter months, outside air may be brought into a building housing an alarm system and heated, producing a large drop in the relative humidity of the air. Very low relative humidity may produce excessive drying of various electronic components, such as capacitors, resulting in equipment failure and concomitant additional maintenance. Consideration should also be given to the possibility of accidents which could release large amounts of steam and result in very high humidities.

Protection against ingress of moisture can be easily obtained by sealing the electronic components of the system. However, sealing will ordinarily not afford complete protection against internal condensation caused by temperature changes, or drying and cracking associated with low relative humidity. Complete humidity protection can only be achieved by hermetic sealing, which may be impractical or incompatible with ventilation requirements for the adequate removal of heat. Consideration should be given, however, to encapsulating sensitive electronic parts such as transistors, integrated circuits, and capacitors in waterproof containers.

Protection against extremes in relative humidity will usually be adequate for protection against dirt, dust, and most corrosive atmospheres. However, in corrosive environments, including ozone produced by radiation, special precautions may be necessary to protect the alarm system against malfunction or failures that would result in excessive maintenance.

Acoustical pressure, shock, and vibration are related mechanical forces to which an alarm system may be subjected. Such forces may in themselves be sufficient to initiate a false alarm periodically; even such a mundane event as the normal closure of a door may, on occasion, trigger a false alarm. Excessive acoustical pressure, shock, or vibration may result in physical damage to the system, or may render it temporarily inoperative. If such forces occur along with an initiating event, as may be the case in a nuclear criticality accident, the alarm may not sound at all, or may be delayed or truncated as a result of the associated mechanical forces. Shock mounting or baffling may be necessary to ensure that the alarm works properly.

2.2.1.4 *Interfering Radiations.* Potentially interfering radiations can be divided into two broad categories:

a. unwanted ionizing radiations, and
b. microwave, magnetic field, radiofrequency, or other nonionizing electromagnetic radiations.

Interfering radiations may act on either the sensor or other parts of the system and introduce spurious signals that may result in false alarms, or conversely, may render the system inoperative. An example might be the accumulation of radon and thoron decay products on a filter paper being monitored by a CAM. If the action is on a portion of the system other than the detector, the effect is termed extracameral. Ionization and concomitant generation of small currents or voltages in cables, capacitors, integrated circuits, transistors, and other electronic components is a relatively common extracameral effect associated with ionizing radiations. As extracameral effects may be absent at low intensities, it may be necessary to verify the operability of the instrument system over its entire operating range to ensure that extracameral effects do not interfere with instrument performance. Radiofrequency and microwave fields may cause similar effects although equipment generating such fields is ordinarily enclosed in metal housings that usually act as an effective shield for these radiations.

Shielding with suitable metals is ordinarily an effective means of eliminating interferences from nonionizing radiation fields. Copper mesh, ferromagnetic metal meshes, and screens of various types may afford adequate protection and still permit the air flow required for cooling and visibility of components. Protection against magnetic fields, if required, is effectively obtained with nickel and iron alloy shielding which is available commercially.

Sensors are particularly susceptible to interfering radiations. Radiation-sensitive detectors may respond to ionizing radiations other than those selected for initiation of the warning signal. For example, a criticality detector designed to initiate an alarm when a predetermined neutron fluence rate has been reached may also respond to ionizing electromagnetic or charged particle radiations. In such cases, protection of the sensor against unwanted ionizing radiations can sometimes be accomplished by suitable shielding. Other methods of eliminating response to unwanted radiations include signal rejection by pulse discrimination or gating techniques, the use of dual compensated chambers, or the selection of another detector.

2.2.1.5 *Radiation Overloads.* Alarm systems should not be rendered inoperative or ineffective at levels beyond the upper end of their effective range. Radiation detectors and associated circuitry should thus not "paralyze" in the event of an overload, at least up to the maximum potential radiation field to which the system may be exposed.

2.2.1.6 *Radiation Damage.* Exposure to ionizing radiation may result in malfunction or damage to sensitive electronic or other components. The dose incurred by sensitive components may result in instrument malfunctions with diverse manifestations or complete failure of the component. For many components, doses on the order of a megarad (10 kilograys) are needed to produce failure. However, modern solid state electronic components are far more sensitive to radiation damage, and failure in transistors and integrated circuits at doses as low as 10^3 rads (10 grays) has been observed (NCRP, 1977; Harrell *et al.*, 1983). Damage is generally a function of the total dose absorbed by the component and occurs irrespective of whether the instrument was operating or not when the exposure occurred.

Care should thus be taken to ensure that the instrument system will survive potential radiation exposures and operate reliably under field conditions. This is particularly true for facilities that produce very high radiation fields such as gamma irradiators or certain accelerators. In these high-radiation environments, even simple components such as switching and wiring can deteriorate rapidly if not chosen and located properly. Shielding may be necessary for components sensitive to radiation damage, but it generally should be considered only if suitable substitutions cannot be made.

2.2.2 *Sensors*

2.2.2.1 *Dynamic Range.* The dynamic range of a sensor and associated electronics should be sufficiently large to result in initiation of the alarm signal at all levels that may be expected in a serious accident.

2.2.2.2 *Precision and Accuracy.* Any uncertainty in the measurement can be an important consideration when the system is used to detect and warn of conditions that may be acutely dangerous or pose immediate hazards to health. At the very least, the system must be able to accurately distinguish between an emergency and a nonemergency situation.

Measurement uncertainty is a function of both precision and accuracy, and should be minimized to the degree practicable. Compensation for uncertainty in response can be accomplished by appropriate adjustment in set point values, with the extreme value of the uncertainty serving as the basis. Set point selection should be established at a level that will ensure alarm activation at the desired confidence level, considering measurement uncertainty. Specific guidance is provided in NCRP Report No. 57 (NCRP, 1978b). Additional information can be found in other references (ANSI, 1978; 1979a; Selby *et al.*, 1972).

2.2.2.3 *Energy Dependence.* In some situations, energy dependence of radiation detectors may pose special problems for the designer of alarm systems. For example, the response of neutron-sensitive detectors may be inversely proportional to the energy of the neutrons. Similarly, photon-sensitive systems may be overly responsive to photons in the energy region below about 100 keV and may also exhibit a sharp energy cutoff in response that is dependent on the material and thickness of the detector wall.

Energy response of photon detectors is frequently compensated for by the addition of shielding material of moderate to high atomic number, which will provide greater attenuation of the low energy photons than of those with energies above about 100 keV. For neutrons, hydrogenous materials such as plastics or other low-Z materials may be used to modify the typical 1/E energy response of some detectors (Hertel and Davidson, 1985). Cadmium, which exhibits a high cross section for thermal neutron absorption, is also sometimes used.

2.2.2.4 *Calibration.* The response of the detector as installed should be established. Calibration frequency with appropriate sources should be consistent with the demonstrated stability of the instrument. This check should be accomplished no less frequently than once per year. Operational checks should be performed more frequently. Energy dependence should be taken into account when calibrating a system. Calibration of the system should be accomplished over the energy and dose rate regions of the radiation to be detected.

The same general principles that apply to radiation sensors also apply to sensors detecting or measuring other quantities. If the sensor requires calibration, it should be accomplished with sufficient frequency to provide the desired accuracy and reliability of the system, but no less frequently than once per year. Operational checks should be performed more frequently, and should be done following maintenance operations or any temporary shutdown of the system, whether planned or inadvertent. For all types of sensors and systems, accuracy standards should be established and maintained such that the effectiveness of the warning system is not compromised.

3. Access Control Systems

Since the purpose of an access control system is to keep personnel from gaining inadvertent access to hazardous areas or to the hazardous condition itself, one of its functions is to provide a warning to facility personnel. The intensity of the warning should be commensurate with the magnitude of the potential hazard. Should the warning go unheeded and the potential hazard be severe, the access control system should prevent access or initiate action to reduce or eliminate the hazard.

3.1 Types of Access Control Devices

There are several devices commonly used in access control systems. These devices provide a warning, prevent access, or initiate mitigating action. The specific devices are described in detail in the following paragraphs. As noted in Section 6.2, an access control system normally consists of a combination of access control devices rather than a single device. The specific combination of devices, of course, depends on the nature and magnitude of the hazard.

3.1.1 *Signs*

Signs that are used as part of an access control system should have a standard format. Unless otherwise specified by law or regulation, the format should include:

a. a heading that indicates the degree of hazard,
b. a statement of the type of hazard,
c. the standard radiation symbol, and
d. a brief statement of instructions.

3.1.1.1 *Headings.* Access control signs should have a heading that indicates the degree of hazard. A CAUTION heading should be used for areas where the risk is limited to receiving unnecessary radiation doses or receiving radiation doses that could exceed permissible limits.

A DANGER heading should be used for areas where there is a risk of immediate injury or death.

Additional information on formatting safety signs can be found in ANSI Z35.1, "Specifications for Accident Prevention Signs" (ANSI, 1972b).

3.1.1.2 *Statement of the Type of Hazard.* The statement of hazard identifies the nature of the radiation hazard. Examples would be RADIATION, ACCELERATOR AREA, RADIOACTIVE WASTE HANDLING AREA, X-RAY MACHINE, etc.

3.1.1.3 *Standard Radiation Symbol.* All signs designed to control access to materials or equipment that emit ionizing radiation should bear the Standard Radiation Warning Symbol shown in Figure 3.1.

The color of the blades and the central disk should be safety purple or safety black and the background should be safety yellow, as specified in ANSI Z53.1, "Safety Color Code for Marking Physical Hazards" (ANSI, 1979c).

The specific shape, and relative dimensions, should be those specified by ANSI N2.1, "The American National Radiation Symbol" (ANSI, 1969). The colors should be durable, and the sign should be replaced if the colors change appreciably.

3.1.1.4 *Statement of Instructions.* Access control signs should have a statement of what actions to take to avoid being exposed to the hazard. Instructions should be limited to those words necessary to convey the message. Lengthy instructions are harder to read and less likely to be read. Some specific examples of access control signs are shown in Figure 3.2.

3.1.1.5 *Illumination.* All warning signs should be provided with adequate illumination so that they are readable. Where illumination

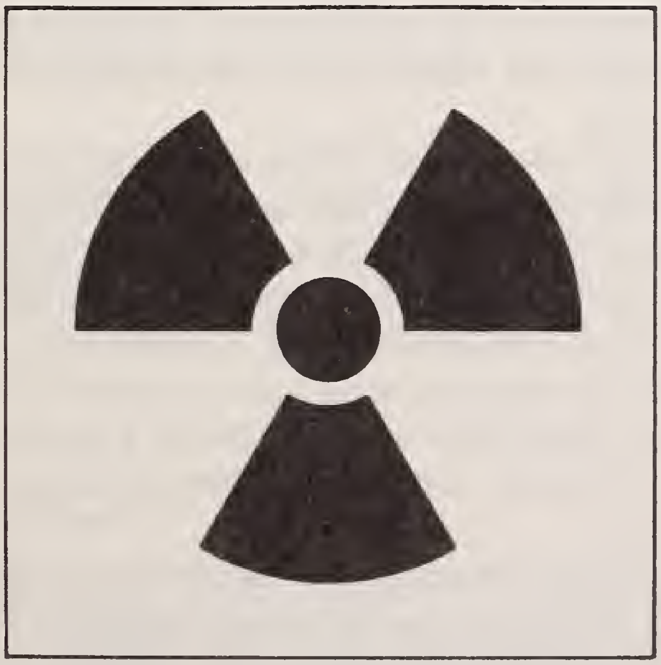

Fig. 3.1. Standard Radiation Symbol.

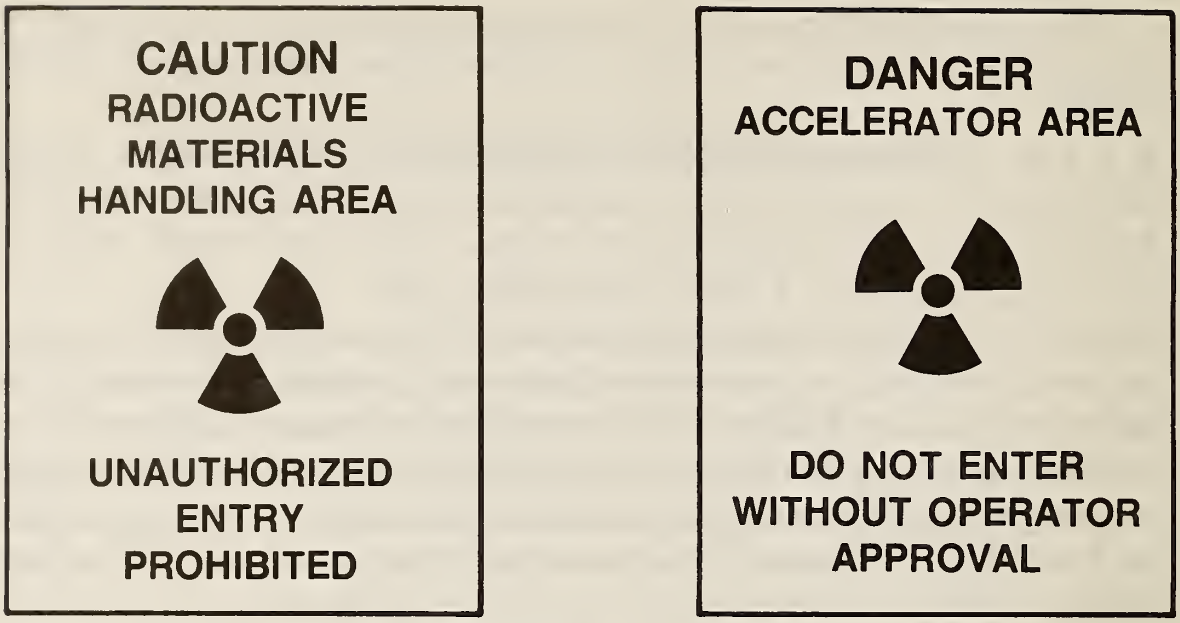

Fig. 3.2. Access Control Signs.

under emergency conditions may be inadequate, emergency lighting should be provided.

3.1.2 *Lights*

Radiation warning lights used as part of an access control system should be magenta, safety purple or red in color. It is recommended that they be flashing or rotating beacons, rather than continuous, to maximize their visibility. Consideration should be given to installing access control lights in pairs so that it is obvious if one of them burns out. Each light should be accompanied by a sign that indicates the purpose of the light and what actions are required. An example is shown in Figure 3.3.

If they are a major component of the access control system, consideration should be given to wiring the radiation warning lights into the interlock system so that if the bulb burns out, or another portion of the circuit fails, the radiation producing equipment will be shut down or the radiation source will be shielded. Consideration should also be given to installing the access control lights in pairs so that they would not shut down the equipment, which might be a major problem in the case of a large accelerator or a medical therapy source, should one of the bulbs burn out.

Access control lights should be of sufficient size and located so that they are readily visible to an individual attempting to enter the controlled access area. The duration of the “off time” in the flashing

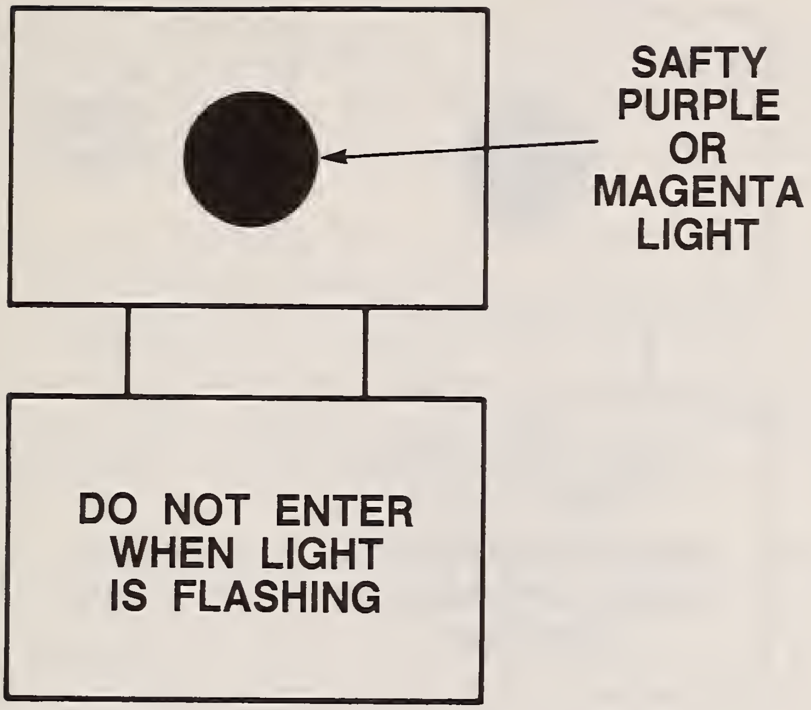

Fig. 3.3. Access Control Light.

cycle is typically about one-half second. The duration of the "on time" in the flashing cycle is typically one to two seconds.

Often flashing lights that are intended to restrict access to an area are accompanied by lights that indicate that access is permissible under certain conditions. Such lights, which should be green in color as specified by ANSI Z53.1, "Safety Color Code for Marking Physical Hazards" (ANSI, 1979c), should be adjacent to the radiation warning lights. As for the radiation warning lights, the access permissible lights should be accompanied by a sign indicating the meaning of the light and what actions are acceptable. An example of this is shown in Figure 3.4.

Often, signs and lights are combined into a single access-control device so that the light provides illumination for the sign. It is desirable that the information on the sign be readily visible (and applicable) only when the light is on. For example, Figure 3.4 could be a transilluminated sign, with the sign being readily readable only when it is illuminated.

3.1.3 *Audible Signals*

Audible signals may be used in addition to visual signals to decrease the likelihood of inadvertent access to hazardous areas. These audible signals should be pulsed to break the monotony of a steady sound.

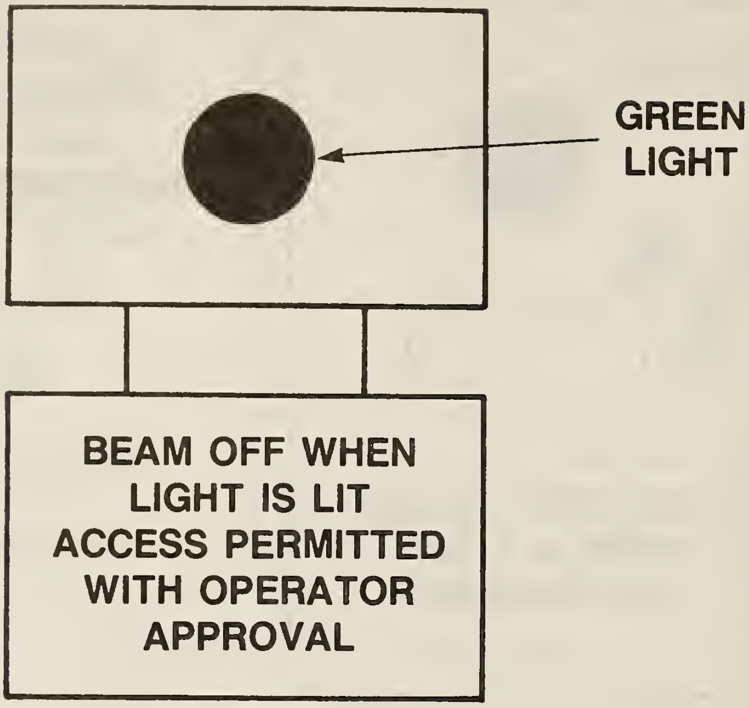

Fig. 3.4. Access Permission Light.

Also, the signal should be loud enough and distinctive enough to be heard over ambient noise levels, but not so loud or irritating that facility personnel are tempted to bypass it. A pulsed chime sound is often found to be satisfactory.

Facility personnel should be familiar with the meaning of an access control signal and particularly how it differs from other warning signals (such as an evacuation signal or a fire alarm). If the facility has unaccompanied visitors or transient workers, they should be briefed on what the various warning sounds are and what action to take when a warning is heard. As for visual access-control signals, audible signals that are major components of the access-control system should be wired into the interlock system so that if they fail, the radiation-producing equipment will be shut down or the radioactive source will be removed to a shielded location. If this is impractical, the audible alarms should be tested on a routine basis.

3.1.4 *Physical Barriers*

Access control barriers can range from something as simple as a rope to something as complex as a locked and interlocked concrete door. The intrusion protection of a barrier should be commensurate with the magnitude of the potential hazard. Barriers that are used only to delineate an area should be of a physical size and color and so positioned that they are readily visible.

Often barriers, in addition to providing access control, serve as the requisite shielding around radiation sources to reduce the radiation levels in occupied areas to acceptable levels. Barriers should be equipped with appropriate access control signs, which are described in Section 3.1.1.

Barriers that are designed to control access to areas in the high, very high, and extreme potential dose categories (see Section 6.2) should be of sufficient size and strength to exclude accidental or inadvertent access. Also, access to these areas should be secured with a lock. In some cases, the size and weight of a shielded door may preclude accidental or inadvertent access and a lock may not be necessary.

Access to keys (which in this usage would include combinations to locks and security cards) to physical barriers should be restricted to authorized personnel. A key that permits access to a very high or extreme potential dose category area should be the same key required at the control console to turn on the radiation-producing equipment or to expose the radioactive source. Such an access control key should not be removable from the control console unless the radiation-producing equipment is turned off or the radiation source is returned to its shielded enclosure. Spare access control keys should be kept under lock and not be available for use without approval of the facility manager.

An example of an acceptable key access control system is one in which the same key is needed to (1) expose the radioactive source or activate or deactivate the radiation-producing equipment at the control console, (2) permit access to the potentially hazardous areas, and (3) reset any run-safe switches (see Section 3.1.6) to the run position as part of a startup procedure. The use of duplicate keys should, of course, be prohibited, since that would completely undermine the safety provided by such a system.

In most radiation facilities, doors are the primary access points into controlled areas. When designing a door or other penetration in a shielding barrier consideration must be given to the need to ensure that the integrity of the shielding barrier against radiation is maintained. For example, unless a maze is used, the door should provide the same equivalent thickness as the rest of the barrier. Typical materials used in doors that must provide significant radiation shielding are concrete, steel, and lead. Functional considerations for shielding doors are given in Section 3.2. General design considerations for shielding doors are given in NCRP Report No. 51 (NCRP, 1977).

In many large accelerator facilities, there are often multiple target areas. It is often desirable to gain access to one target area when the beam is directed into another target area. In this instance, the beam control system, barriers, and key systems must be designed to prevent the inadvertent production of high radiation levels in the occupied target areas.

3.1.5 *Interlocks*

Areas containing radiation-producing equipment or sources that could produce potential doses in the high-to-extreme categories (see Section 6.2) should have interlocks as an integral part of their access control system. An interlock is a device that automatically reduces the exposure rate upon entry by personnel into a high-radiation area. Also, interlocks prevent the production of high levels of radiation unless all of the barriers are in place. Interlocks are mounted on doors, gates, shutters, movable shields, or other barriers, or under pads on the floor.

Specific design and operational considerations relating to interlock systems include the following:

1. Interlocks should be "fail safe"; that is, in their most likely failure modes, they will prevent the production of high radiation levels in potentially occupied areas,
2. Each access control barrier to radiation areas that are classified in the very high or extreme potential dose category (see Section 6.2) should be equipped with two independent (redundant) interlocks connected so that either will perform its function in case the other interlock fails,
3. It should not be possible to resume the normal operation of the radiation source simply by closing the interlock once it has been opened. The opening of an interlock should trigger a requirement to reinitiate the startup procedure, which would involve searching any controlled access areas that may have been opened when the interlock was broken,
4. If the design allows the interlock to be bypassed under certain controlled conditions, there should be a built-in timer so that the bypass is automatically removed after a designated period of time. The bypass switch should be accessible to authorized personnel only. In some cases, an acceptable alternative to the use of a timer for an occasional interlock bypass is the use of administrative procedures that are carefully followed and documented in the operations log,
5. Interlocks should not be routinely used to turn off radiation-producing equipment. The failure of an interlock under these circumstances can have serious consequences.

Figure 3.5 gives the room layout and circuit diagram of an interlock system that meets these design considerations. In this example, the source is normally removed from and returned to its shield using a power-operated source control mechanism. Removing power from the controls will allow gravity or a spring to return the source to its shield. In normal operations, the operator would close the run/safe switches while searching the room. Upon leaving the room, he would press the start-up enable switch near the door, thus closing contact K1-1. Contact K1-1 is held closed by the action of coil K1 . This time delay relay would remain closed for a set time after the start-up enable switch was pressed. If the operator closed and locked the door in the set time, then contact K2-1 would close and remain closed by the action of coil K2 , provided that all the interlocks and the door key switch remained closed. At the same time, the start-up notification would be activated. The operator would then close the source key switch, using the door key to apply power to the source control mechanism.

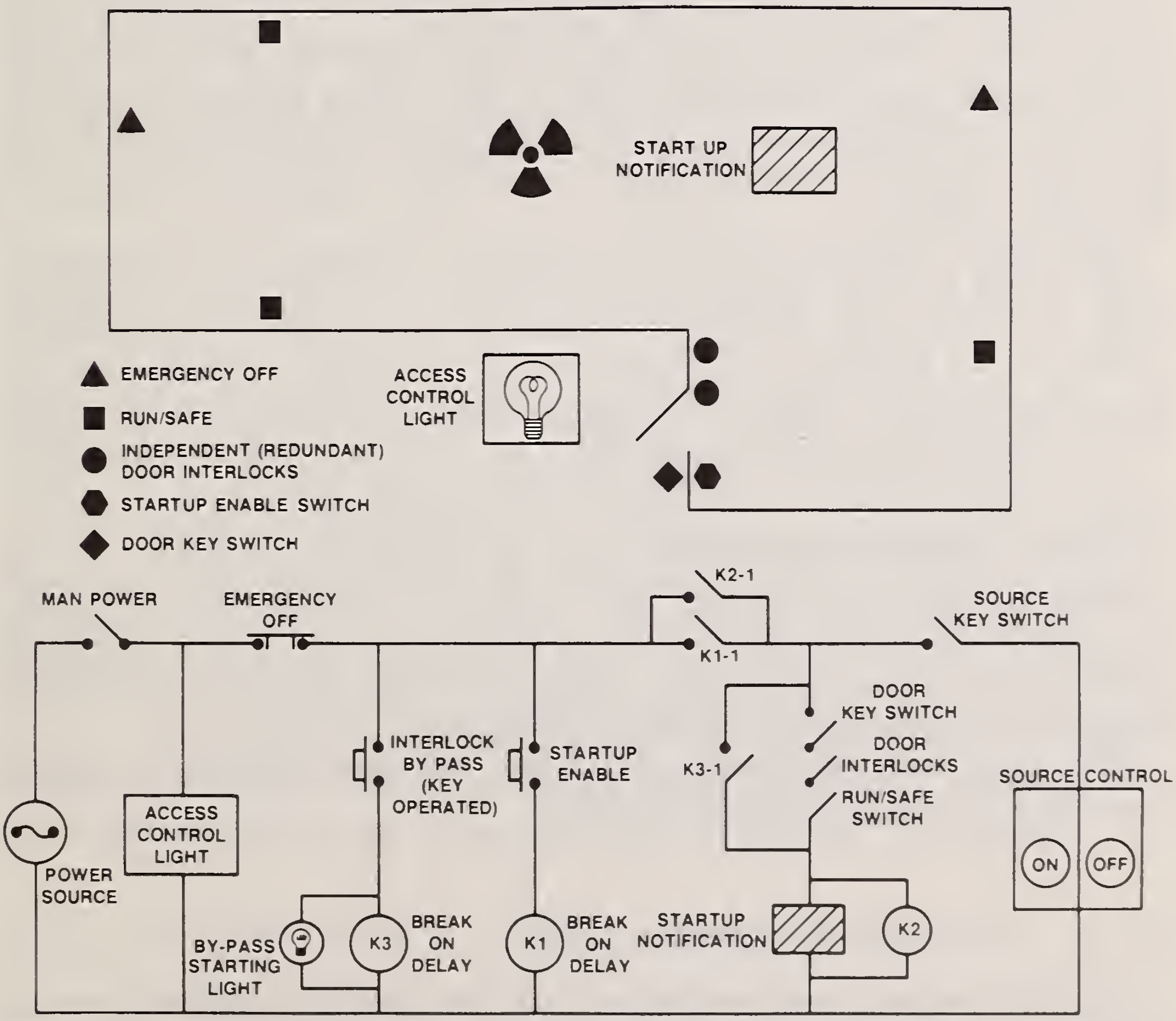

Fig. 3.5. Typical Interlock System.

Opening any interlock would remove power from the source control mechanisms by deactivating coil K2 , thus opening contact K2-1. In order to reapply power, it would be necessary to repeat the entire procedure.

Provision is also made to bypass the interlocks by activating contact K3-1 by the action of coil K3 , which would remain closed for a set time and then automatically remove the bypass.

3.1.6 *Run/Safe and Emergency Shutdown Switches*

Large or complex radiation exclusion areas should be equipped with switches that can (1) preclude starting up radiation production (run/safe switches), or (2) effect an emergency shutdown, or (3) do both in the event that an individual is inadvertently caught within an exclusion area during pre-start-up or actual radiation production operations.

The run/safe switches are designed to be set routinely to the safe position by personnel reentering an exclusion area after ceasing radiation production operations. They prevent radiation production operations from starting until they have been manually reset (preferably with a key) to the run position. It is good design practice to require that all run/safe switches in a controlled area have to be reset to the run position before start-up if any one of the switches has been set to the safe position.

Manually operated emergency shutdown switches, which immediately terminate the production of radiation or move the radiation source to its shielded enclosure, should be placed conspicuously in areas that contain high-to-extreme potential radiation hazards. These switches should be readily accessible so that an individual inadvertently caught within an exclusion area during prestartup or actual radiation production operations can shut down the operation, if that is more expeditious than exiting the area. (Interlocked exit doors can be considered to provide the same protection as emergency shutdown switches for some facilities.) Unlike run/safe switches, emergency shutdown switches are designed for emergency use only.

Run/safe and emergency shutdown switches should be clearly marked as to their intended function.

3.1.7 *Prestartup Notification System*

Radiation areas from which personnel are excluded during normal operations should be inspected before starting up radiation-producing equipment or introducing radiation sources. Visual observation is useful for determining whether personnel are cleared from an area if the facility is small and vision is unobstructed. For larger facilities, the clearing or searching procedure is necessarily more complex and should always involve the resetting of run/safe switches to the run position.

In large or complex facilities, particularly for those with high-to-extreme potential dose category areas, a thorough search should be made before operations begin. The search should require that the searcher activate, within a set time period, a run/safe switch at each of several stations in the area to be cleared. If the run/safe switches are not activated within the set time interval, then the sequence must be initiated again. Precautions should be taken to ensure that other facility personnel are kept from entering an area while it is being searched. This may require that an additional person be stationed at the door to the area being searched to prevent the inadvertent reentry of facility personnel.

After the search sequence has been completed, a notification should be made that radiation-producing operations will begin. The notification should consist of dimming the lights in the potential radiation hazard areas to get the attention of any personnel who might have inadvertently been left in those areas following the search. Sufficient illumination should be retained so that an individual can reach the emergency shutdown switch. The dimming of the lights should be followed by a verbal announcement or warning sound, or both, indicating that the production of radiation is going to begin in the area. There should be sufficient time delay, typically at least 15 seconds, between the time of the initiation of the start-up notification and the time radiation production actually begins to allow an individual in the area to reach an emergency shutdown switch or exit the area.

Under some circumstances, it is necessary for personnel to have access to radiation hazard areas during the operation of the radiation-producing equipment for purposes of beam alignment, equipment checkout, or maintenance. Such operations should only be permitted under carefully controlled conditions. The conditions should include strict access-control requirements and the regulation of parameters affecting radiation production so that radiation doses received, if any, are below regulatory limits and as low as reasonably achievable.

3.1.8 *Dosimeter Readout*

It is possible to incorporate thermoluminescent dosimeters (TLDs) into access control systems. Such systems would normally be limited to access controlled areas where substantial radiation doses (compared to radiation standards) could be received during routine operations. This system would require the individual to insert his TLD into a computerized reader before entering a controlled area. If his prior accumulated dose in addition to the dose recorded on his TLD (if any) exceeds a preset limit, then access would be denied.

Access control using self-reading pocket dosimeters could also be used for this purpose. In this case, cumulative radiation doses and access status would be monitored administratively.

3.2 Functional Considerations

3.2.1 *Power Requirements*

The power requirements of access control systems, *i.e.*, requirements for lights, doors, and audible signals, generally are met by the electric power outlets, which in the United States are usually provided with 60 Hz power at 115–120 or 230 V, single phase. (See Section 2.2.1.1 for an additional discussion of electric-power requirements.)

Failure of electric power to an access control system can be a serious matter. In many instances and particularly for machine-produced radiation, the radiation hazard is eliminated if the primary power fails. However, radioactive sources and radiation from induced radioactivity may continue to be a significant hazard even in the event of a primary power failure.

For areas that might contain high-to-extreme potential radiation dose categories (see Section 6.2), the access control system should be provided with emergency power. Also, if power is lost to the access control system, radiation production should be terminated automatically.

In the design of a system, it is necessary to consider what would occur in case of a power failure. For example, it should be possible to open an access control door from either side even in the event of the loss of power. In most radiation facilities, access control doors are operated manually. For some situations, however, a door or barrier too heavy for manual operation requires external power. Some barrier-opening mechanisms require direct electric power, whereas others require air pressure. Provisions should be made for manual operation in case of power failure.

3.2.2 *Environmental*

The design of an access control system for a radiation facility should take into account the full range of environments in which the system may operate. A number of environmental factors, either singly or in combination, may adversely affect the operation of the access control system. The devices used for access control—*i.e.*, doors and other types of barriers, both with and without keys, lights, signs, lighted signs, and audible signals—should be designed for high reliability and should not require frequent servicing. They should also be designed to minimize the effects of nonuse, deterioration, power surges, and other adverse environmental conditions such as:

a. temperature,
b. moisture,
c. ambient pressure,
d. corrosive atmospheres,
e. acoustical pressure,
f. vibration,
g. shock,
h. dirt, dust, and
i. mechanical damage by pests.

The access control systems should be capable of operation over the range of environmental conditions to which it will be subjected during normal and emergency (*i.e.*, accident) conditions. See Section 2.2.1.3 for a detailed discussion of environmental effects and Section 2.2.1.6 for radiation damage effects.

4. Protective Function Logic Systems

4.1 General

Protective function logic systems are an integral component of many access control and alarm systems. They translate the input signals from radiation detectors, interlocks, or other sensors into warning signals and/or actions to eliminate or significantly reduce exposure of personnel to hazardous levels of radiation. A logic system can be activated by information from input devices such as radiation or nonradiation sensors or signals from access and process controls. It can also be activated by failures of input or output devices or by failure of the logic system itself. The logic system should not permit start-up and operation of a radiation facility until all safety system components are operational.

Logic systems are not required where the potential dose can be categorized as minimum or moderate (see Section 6.1) but are recommended where the potential dose is very high to extreme.

Logic systems may consist of relays, solid-state electronics, computers, programmable controllers, or a combination thereof. They should be of fail-safe design so that protection functions are initiated in case the system fails in its most likely failure mode. The system components should be of a reliable design and construction. Where possible, each component should be of fail-safe design.

Nuclear power plants are not specifically addressed. All aspects of nuclear power plant protective function logic system design are subject to specific NRC regulations. The information provided here may be applicable to some aspects of research type nuclear reactors.

In installations where the potential for high-to-extreme radiation doses exist (see Section 6.2), redundancy of components, subsystems, or entire logic systems must be considered. Redundancy is necessary despite the use of fail-safe design if the system must function in case of any type of failure. Completely redundant systems should not have any component in common since failure of that component could disable both logic systems. In some situations, it may be acceptable to use redundancy to ensure the operation of complex or vulnerable components or subsystems while employing extremely reliable components for common elements. Another use of redundancy is to reduce the incidence of false alarms due to spurious signals. In this application, two or more channels must sense the hazard in order for the protection function to be initiated. It is important to recognize that this application of redundancy reduces the system reliability since failure of one channel will disable the entire protection logic system. It is, however, possible to combine these two applications of redundancy to achieve some of the advantages of both.

In the case of older style relay-type systems, it is common to use three or more redundant channels. At least two of the channels are required to initiate a protective function either by channel failure or actual alarm. This design offers the optimum in terms of actual hazard detection while reducing spurious protection function initiation. In the case of software-based computerized protective function logic systems, dual redundancy may be sufficient to achieve the necessary safety and operational reliability.

For radiation-producing facilities having very complex control systems, it may be desirable to install special circuitry that continuously monitors the operation of logic system circuits to warn of possible circuit failure. Means can also be provided to permit checking of the monitoring circuits. For example, one of the easiest methods is to compare the output of the two parallel systems (Hartin and Goodman, 1971). This can be accomplished by taking advantage of microprocessor and programmable controller technologies that have built-in features to perform circuit and component integrity checks and to diagnose failures when they occur.

Manual reset of the logic system should be required after it has been activated and has performed a protective function. Normally, restart should be allowed only after the problem that causes a shutdown has been diagnosed and corrected.

In some situations, a logic system may initiate the operation of several pieces of equipment to eliminate or reduce radiation hazards. The system should be designed to ensure that the sequence and timing between each of the events is proper. Provision should be made to permit manual activation of the protective functions should logic systems fail.

Before start-up of a new facility, it is necessary that the logic system be completely reviewed and tested to ensure that it functions as designed. Any subsequent system modifications, such as component substitution or circuit changes, should not be made until they have been reviewed and approved by a safety review group made up of appropriate qualified personnel. Following modification, the system should be tested to ensure that it functions properly before returning the facility to operation. All such modifications should be documented.

Although it is not always possible to protect logic circuits from deliberate or inadvertent alterations that will preclude proper functioning, every reasonable effort should be made to prevent such alterations. Access to system components should be restricted to personnel authorized to use and maintain the system. During maintenance periods, tagging procedures should be used at affected component and control console locations to inform all personnel that the facility should not be operated until maintenance is completed. Where possible, equipment rooms and control rooms should be locked when not attended. Key control should be assigned to the facility manager.

Software-based protective function logic systems are becoming more widely used. It is *imperative* that such systems be carefully evaluated for proper function and for potential failure modes before they are operated. Also, software and hardware protection mechanisms should be implemented to inhibit accidental or unauthorized alteration of the software. These protection mechanisms should remain functional following a power interruption or in case of unauthorized access to the control system.

An example of a simple logic system using two radiation detectors and two switches on a single entrance door is shown in Figure 4.1. This logic system is totally redundant and will shut down the radiation

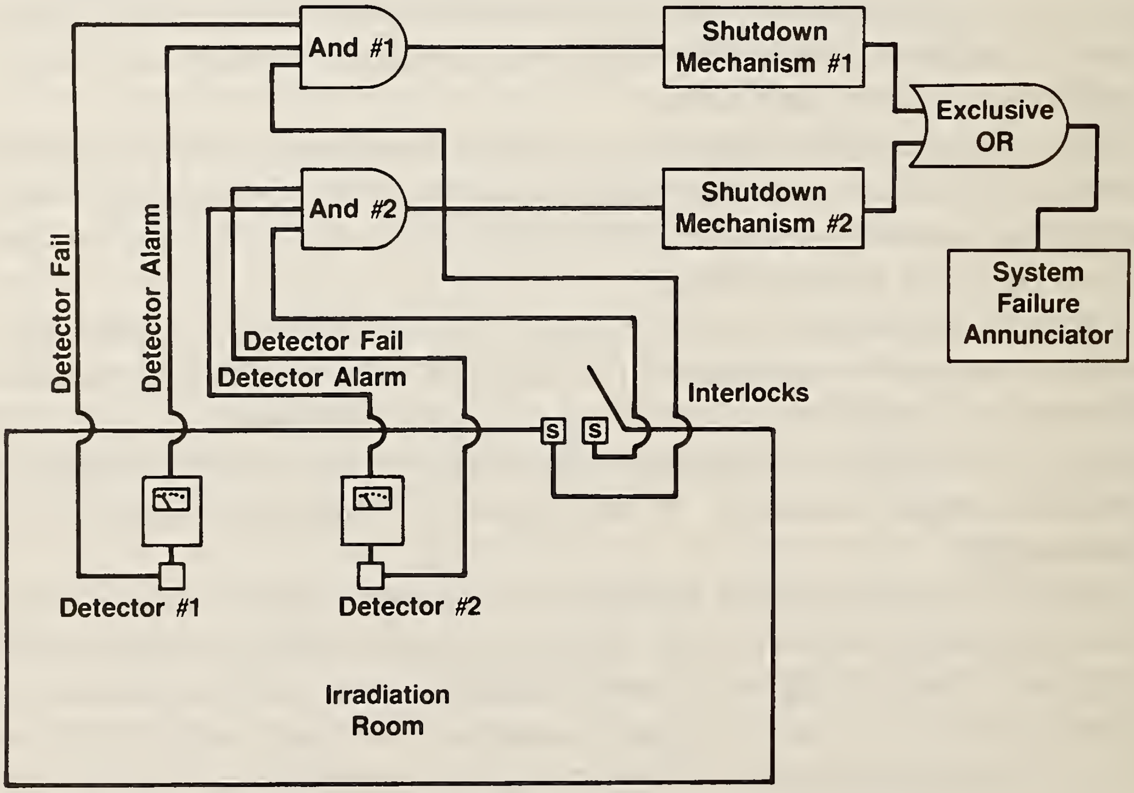

Fig. 4.1. Circuit Diagram of a Typical Protective Function Logic System.

source if either of the radiation detectors fails or gives a reading above the alarm point. It will also shut down the radiation source if either of the interlocks indicates that the door is not closed. The safety logic system employs electronic circuits that function as AND and OR gates. Detector #1 and one of the door interlocks send signals to AND gate #1. Detector #2 and the other door interlock send signals to AND gate #2. For the radiation source to be operational, the signals to each AND gate must indicate the door is closed and the radiation is neither too low, indicating detector failure, nor above the alarm set point. If either AND gate does not receive all three correct signals, the appropriate shutdown mechanism is activated. If the shutdown mechanisms #1 and #2 do not receive the same signals, then the exclusive OR gate is activated indicating a possible failure in one of the shutdown circuits. For example, if detector #1 fails, shutdown mechanism #1 would be activated through AND gate #1. This would activate the system failure annunciator through the exclusive OR gate.

The radiation levels at the radiation detectors could be very high when the radiation source is operational. In this case, it would be necessary to design the logic system to prevent the high radiation readings from shutting down the radiation source, assuming that the remainder of the interlock chain is designed and operated properly.

4.2 Sealed Source Retraction

In facilities where radioactive material in sealed source form is used for irradiation purposes, such as in gamma irradiators, the primary method of reducing radiation levels is to return the source to a shielding enclosure. In these facilities, provisions should be made for radiation detectors to monitor radiation levels in areas outside the irradiation room occupied by personnel. Should hazardous levels of ionizing radiation be detected, the radiation sensing device should activate a logic system that will, in turn, activate or deactivate systems to return the sealed source to the shielded enclosure. Access control devices should also be installed to prevent access to the irradiation room and to initiate source retraction when entrance is attempted with the sealed source in any position other than the fully shielded or retracted position. The sealed source should be automatically retracted in the event of a power failure or failures of the radiation sensing device, access control devices, or other logic system components. The logic system should also activate warning devices and be part of the circuitry verifying that the sealed source either has been retracted or is in the "irradiate" position.

For irradiators such as medical radiation therapy units, the source, when not in use, is normally maintained in a fully shielded position by mechanical springs. To move the source to the "irradiate" position, the source movement electrical circuitry and components are activated. To return the source to the shielded position, the source movement electrical circuitry is deactivated by the logic system, thereby allowing spring action to retract the source.

In a large irradiator facility, such as a food irradiator or a medical products sterilization facility, the source, when not in use, should normally be maintained at the bottom of a water storage pool by the force of gravity. To raise the source to the "irradiate" position above the storage pool, an electrically or pneumatically operated hoist is used. To return the source to the shielded position, the electric circuitry or air supply system is deactivated, thereby allowing gravity to return the source to the bottom of the storage pool. The logic system may incorporate a pool water level monitoring device that provides input to the logic system to prevent access to the irradiation room unless the water level in the storage pool is of sufficient depth to shield the source adequately.

Limit switches should be provided at both the "irradiate" and the fully shielded positions. They should be incorporated into alarm device circuitry that informs personnel of the source position. It is recommended that the logic circuit include timing capabilities so that if the source does not reach its "irradiate" position within a normal specified time (indicative of equipment malfunction), the logic circuit will automatically initiate source retraction.

4.3 Shielding Insertion

In radiation-producing equipment where collimated beams may create a radiation hazard, insertion of shielding is the primary method used to reduce or eliminate hazardous radiation. Examples of such equipment are x-ray diffraction devices and industrial ionizing radiation gauging devices using either electrical means or sealed sources of radioactive material to produce the radiation beam. Here, shutters, consisting of dense shielding material, are built into the equipment to close and absorb the beam at the appropriate time to prevent exposures to personnel. The shutters should be designed so that they are maintained in the "closed" position by the force of gravity, by the force from redundant mechanical springs, or by other positive closure mechanisms. Shutter position switches activated by an integral part of the shutter should be installed and should activate indicating lights or mechanical indicators that show whether the shutter is "open" or "closed." Upon failure of the indicating lights or the shutter position switches, the logic system should initiate shutter closure.

Appropriately positioned microswitches connected into the logic system should initiate or maintain shutter closure whenever shielding panels, collimators, beam stops, or other equipment containing or shielding the beam are removed or not positioned properly. The logic system should also prevent operation of the system unless all the necessary equipment is in place and all the indicating lights are operational. In case of a power failure, the logic system should also initiate shutter closure.

Because of the difficulty in positioning radiation sensors properly to detect the presence of scattered or collimated beams and the insensitivity of most sensors in detecting the low-energy beams frequently characteristic of such radiation-producing equipment, most facilities do not rely on radiation sensors as a part of the logic system. However, the use of radiation detectors should be considered because development of miniaturized and low-energy-sensitive radiation sensors continues to improve the practicality of using them. Should a radiation detector be used, it should initiate shutter closure through the protective logic system whenever hazardous radiation levels are detected. Shutter closure should also occur automatically if the radiation sensing device fails. The use of a radiation detector in a cobalt-60 teletherapy facility is discussed in Appendix B.

4.4 Electronic Device Shutdown

In those facilities where ionizing radiation beams are produced by electronic devices, it is necessary to provide means to minimize the possibility of personnel being inadvertently exposed to hazardous levels of radiation. Examples of such devices would be particle accelerators, x-ray units, or electron beam or electron microscope units having electron energies in excess of 25 keV.

Access control devices should be provided that prevent access and initiate automatic shutdown if access to a hazardous radiation area is attempted. Automatic shutdown should also occur if the access control devices fail to function properly. Where a shielding insertion mechanism is used, failure of this mechanism should also initiate device shutdown.

For devices such as particle accelerators and electron beam units, radiation detectors should be installed in areas occupied by personnel where the potential for high-to-extreme radiation dose levels exist (see

Section 6.2). These radiation detectors should initiate device shutdown through the logic system if they detect hazardous radiation levels or if they fail. Startup of the device should be permitted by the logic system only when all safety systems are operational.

In the case of x-ray diffraction units and small electron beam devices, device shutdown can be accomplished almost instantaneously. For large facilities such as particle accelerators, the logic system should be designed to allow access to beam areas only after sufficient time has elapsed to ensure that residual currents and voltages and induced short half-life radioactive materials are no longer present. Shutdown of any of the devices by the logic system should be in a manner that avoids damage to equipment.

4.5 Prevention of Entry

In facilities such as accelerators or gamma irradiators, where irradiation is conducted in a shielded room, access control and logic systems should be installed that prevent entry unless the high radiation levels potentially present are eliminated. In the case of an accelerator, this would mean shutting down the accelerator or diverting the beam to another unoccupied irradiation room. In the case of a gamma irradiator, this would mean moving the source to the shielded position.

Access control points should be equipped with a locked access control barrier that can only be opened by a key controlled by the facility manager. Only one key should be in use at any given time. Ideally, this key should be the same key that is used to initiate start-up of the facility and is inserted in the facility control console off/on switch and turned to the "on" position when irradiation operations are being conducted. Removal of the key from the "off/on" switch should only be possible with the key turned to the "off" position. Some facilities, such as a gamma irradiator, that use a continuously feeding conveyer belt to supply the material to be irradiated into the shielding enclosure, may be very difficult to equip with locked barriers. In this instance, it may be necessary to use other means, such as electronic eyes or pressure sensitive mats, to exclude individuals from the shielding enclosure when the gamma sources are exposed.

In the case of a gamma irradiator, radiation monitoring equipment should be installed inside the irradiation room and operated whenever personnel are in the room. It should be capable of alarming if significantly increased radiation levels are detected. If the increased radiation levels are the result of irradiator start-up, the monitor should shut the irradiator down. Since the doses to radiation sensors in an irradiation room could exceed a megarad (10 kilograys), the potential effects of radiation damage should be considered (refer to Section 2.2.1.6). In addition, an emergency shutdown switch, emergency pull cable, or interlocked exit door should be available in the irradiation room to shut down the facility. Manual reset should be required before facility start-up. (Also refer to Sections 3.1.6 and 3.1.7.)

The logic system should require a specified sequence of steps before allowing access to the irradiation room. When very high or extreme doses (see Table 6.1) are possible, consideration should be given to using a sequence requiring successful testing of the irradiation room radiation monitor before personnel are able to enter. A portable survey meter that has been checked for proper operation should be carried when entering the irradiation room.

A run/safe switch should be installed in the irradiation room that can be set to the "safe" mode either manually by personnel or automatically by the logic system to prevent startup of the irradiator whenever personnel are present in the room. The run/safe switch must be manually set to the "run" mode before start-up to ensure that the room is physically searched and cleared of personnel. If the room is large or if there are obstacles to vision, more than one run/safe switch may be necessary to ensure that the entire room is searched.

Activation of the main off/on switch should initiate a logic system timer that will not allow start-up of the facility unless all sequential start-up steps, including closing of access control barriers and actual start-up, are carried out within a specific time interval.

Activation of the main off/on switch should also initiate visible and audible alarm devices both within the irradiation room and in the control console area to ensure that personnel are aware that start-up of the facility is being initiated. Additional audible and visual alarm devices should be used at the control console area to alert personnel to the operational status of the facility.

5. Reliability

5.1 Fail-Safety

Because of the potential for acute radiation exposure with possible life-threatening or other serious consequences, radiation alarm and access control systems must operate with a high degree of reliability. Not only must their performance be near perfect, but in the unlikely event of failure, the logic should attempt to assure that safety is maintained. Failure of any component, loss of power, or external interferences should not result in an unsafe or potentially unsafe condition, which in the case of an alarm or access control system could result in a hazardous radiation field without suitable warning or means to exclude personnel.

As applied to radiological situations, fail-safety is generally accomplished by appropriate system design that attempts to prevent or terminate the radiation field in the event the system as a whole or any key component becomes inoperable or fails to function as desired. Fail-safety thus refers to the ability of the system as a whole to return to safe (*i.e.*, nonexposure) conditions in the event of a failure or inoperability of a key component (*e.g.*, the warning alarm system). In a fail-safe system, the radiation source is shut down if component or circuit failure associated with the safety system occurs. Perfect fail-safety is achieved when the access control or alarm system cannot fail to perform its intended function for any reason. In practice, perfection is unattainable since components can fail in their less probable, but unsafe, failure modes. Reliance must be placed on other means, commonly electronic, to try to ensure that fail-safety will be achieved.

Numerous fail-safe designs have been described in standard engineering textbooks and in the literature. In general, these are based on electromechanical relays or pneumatic logic elements and are usually fully adaptable to radiation warning and alarm systems with little or no modification (Bramson *et al.*, 1976). One of the simplest and most effective fail-safe mechanisms is the use of electromagnetic switches or other electromagnetic devices which, if not provided with a suitable signal, will open, and thus, shut down the radiation generating apparatus. It is a relatively simple matter to provide one or more such switches energized by the alarm and warning system in the radiation start-up or initiation circuitry. If a failure occurs in the alarm or warning system, the appropriate voltage will no longer be supplied to this switch, resulting in an open circuit that prohibits the start-up or that shuts down the system.

Unfortunately, it is possible, though less likely, that a different mode of failure might occur in which the appropriate voltage will still be applied to this switch. Thus, a more accurate description of fail-safe is the ability of the system to return to a safe condition in the event of a failure of a key component in its most likely failure mode. For higher reliability where the small probability for these less likely failure modes is considered unacceptable, other concepts such as redundancy, must be considered.

5.2 Redundancy

Redundancy of components is widely used in the nuclear industry to enhance reliability by increasing the probability that the system will function properly, and to mitigate the effect of failure of key components. The decision as to which components should be duplicated rests in large measure on judgments based on reliability and failure criteria and statistics. Generally, however, redundant power supplies are provided in the form of the primary power source and the secondary or backup source (see Section 3.2.1). Other commonly redundant features and components may include the detector or sensor and the alarm. Depending on the criteria for reliability, redundancy of the entire alarm or access control system may be needed to ensure that an acceptable probability of proper operation of the safety systems will be achieved.

Redundancy can be used to enhance both system reliability and fail-safe design (Ida, 1983). Exceptional reliability can be achieved through use of parallel redundancy in which system failure occurs only after concurrent failure of all the parallel elements. Similar logic can be used to achieve a fail-safe situation (see Appendix A for a discussion of reliability).

5.3 Maintenance

A regular preventive maintenance program should be developed and implemented to minimize the potential for failure and to ensure that system operability is maintained. The frequency and thoroughness of the maintenance program should be based on the complexity of the access control or alarm system and the degree of the potential radiation hazard. Simple access control or alarm systems for minimum to moderate potential radiation dose areas (see Section 6.2) would normally require only a minimal maintenance program. More complex access control or alarm systems for high-to-extreme potential radiation dose areas would require a more comprehensive maintenance program. Since maintenance often involves activities and procedures different from those in normal operations, care should be taken to minimize the possibility that an accidental exposure will occur during maintenance operations.

Maintenance schedules are best developed on the basis of operating history or known component behavior, but these data are frequently unavailable, particularly for systems of unique design. However, such data can be developed for many systems by accelerated aging techniques (Gwyn, 1982; Johnson, *et al.*, 1983) and by careful collection and analysis of maintenance and repair data, with the intent of determining the mean time before failure (MTBF) for the system as a whole as well as for key components. The MTBF is the reciprocal of the sum of failure rates of the individual components of the system and, as such, is an important measure of reliability as well as being the basis for establishing the time interval between preventive maintenance operations (Rooney, 1981). (Refer to Appendix A for further discussion on reliability.)

For simple systems, the most critical component, and the one that will determine the overall MTBF for the system as a whole, is often the radiation sensor, which typically has a failure rate on the order of 10 to 60 per million hours of operation from all failure modes (IEEE, 1977). At the upper limit of 60, this corresponds to about one failure per 16,000 hours, or, on the average, about one failure per two years of continuous operation.

Accurate records should be kept of any maintenance and repair work performed on the system, including specific descriptions of what was in fact done, the date the work was perfomed, the date the equipment was removed from and returned to service, and by whom the work was performed. The records should be kept not only for legal purposes but also to establish a data base that can be used for evaluation of system performance.

5.4 Tamper Resistance

In addition to being protected against natural environmental conditions, alarm and access control systems should also be protected against deliberate or accidental intrusion. This will enhance reliability and reduce the possibility that alarms or access controls will be bypassed or otherwise rendered inoperative.

Tamper resistance can take many forms, ranging from simply placing equipment in locations that are not easily accessible, such as high up on a wall, to isolating the system within a locked enclosure. Intermediate measures include the use of seals and warning indicators that show when a panel has been removed or access to circuitry has been gained.

5.5 Testing and Internal Diagnostics

It is highly desirable for alarm systems to be equipped with the internal diagnostics or sensors that continuously monitor the ability of the system as a whole, or at least key subsystems and components, to perform its intended functions, and to provide indication when a failure has occurred. For systems using radiation detectors, this can sometimes be accomplished by monitoring background radiation or by installing a small radioactive source of sufficient strength to provide a continuously measurable signal. If this background measurement falls below a certain predetermined level, a failure alarm will then be triggered. Continuity and feedback circuitry can also be used in conjunction with failure alarm circuitry, as can the insertion of electronic pulses at various points within the circuit. Various types of audit circuitry can also be used periodically or continuously to evaluate certain parameters, such as voltage wave form or pulse duration, or continuity or conductivity within specific circuits or components. Note that the latter methods do not provide a check of the operability of the detector.

In addition to internal continuous test circuitry, systems can be provided with various kinds of test circuits that require manual initiation. Examples of these include the means of manually producing a test signal to the alarm to verify its operability, and manual activation of an internal circuit that produces a voltage pulse or signal comparable to that from the detector. The latter provides a good means of testing the entire system, excluding the detector.

The system should be tested periodically; the frequency of testing should be related to the complexity and demonstrated reliability of the access control or alarm system, but it should be done no less frequently than once per year. Operational checks are normally the least rigorous and are designed to provide verification of the operability of the system. In their simplest form, operational checks may be simple electrical continuity, frequency, or voltage tests establishing that the system is capable of performing only a very basic function. More typically, operational checks verify that the system is performing the intended operation, but without regard to whether the performance is within the bounds of the prescribed specifications. Operational checks are usually performed quickly and with a minimum of external instrumentation or equipment.

More rigorous tests can be performed to ensure that the system is in fact operating within established parameters for accuracy, precision, response time, and numerous other variables. At the most rigorous level, testing may be carried out to verify that the system and its various components are operating within the range of prescribed specifications, and it thus may include complete calibration and require extensive and sophisticated external equipment.

Testing is best accomplished by external means. A common form of testing is to activate the sensor by means of an external source—radiation in the case of radiation sensitive systems. Partial tests of the system accomplished by introducing at some point in the system a signal mimicking that from the detector does not provide an adequate test of operability under field conditions.

6. Criteria for Selecting Alarm and Access Control Systems

6.1 Potential Radiation Dose and Access Requirements

The safety analysis of a radiation facility should include an evaluation of the potential dose equivalent rates and levels of airborne radioactive material in areas where personnel may be required to work. These potential radiation fields or radioactive material levels may be the result of normal operations (*i.e.*, radiation in a target cave) or the result of an incident that degrades the safety of the work environment (*i.e.*, the breach of a glove box). On the basis of the safety analysis, areas can be selected (1) to which access should be controlled during normal operations, and (2) for which alarms to facility occupants should be given if the safety of the work environment becomes degraded.

The potential dose equivalent rate for both normal operations and incidents will depend on the type(s) of radiation sources used at the facility. Those that may be encountered at various facilities range from less than 100 mrem/h (1 mSv/h) to more than 10^5 rem/h (1 kSv/h). The potential dose equivalent rate is a primary factor in determining the potential risk to personnel, but it is not sufficient by itself. An estimate of the potential dose equivalent per occurrence should be made. This requires that the potential exposure time be estimated. The time an individual could be exposed or the time a failure could persist before detection are difficult factors to evaluate. Reliability of systems, including operating procedures, facility use, personnel surveillance, and system redundancy are factors that must be considered in arriving at a potential exposure time. The potential dose equivalent rate, the potential exposure time, and the portion of the body exposed combine to give an estimate of the potential effective dose equivalent.

The same criterion can be used for selecting access control and warning systems for facilities where internal exposure is possible. In this case, the potential committed effective dose equivalent should be calculated based on an assumed exposure scenario using the protocol of Publication 26 (ICRP, 1977) and Report No. 84 (NCRP, 1985). The protocol is used to arrive at an estimate of risk whether the irradiation is partial or whole body. Internal and external doses should be summed to obtain the total effective dose equivalent.

The dose categories, as a function of potential effective dose equivalent, are given in Table 6.1. The dose categories are based on dose equivalents measured in rem (or sieverts) to provide a measure of long-term risk. However, since most accidental external doses will be received in a short time, any estimate of acute effects would be more accurately based on the potential absorbed dose in rads (or grays) (NCRP, 1971).

Access requirements for potentially hazardous radiation areas will vary depending on the type of process used at the facility. Irradiation facilities may have their processes automated so that access is required only for routine maintenance and emergencies. Medical facilities using accelerators and sources for therapy may require frequent access to accommodate patient needs. Research installations may have unique access requirements for experimental areas. Access control systems for these facilities protect against entry into areas where a large portion of the body could be exposed.

There are situations, however, where the radiation field may be limited to a small area. X-ray diffraction units and beamlines from accelerators and storage rings are examples of high-intensity, small-area exposures. If the intensity is extremely high, these limited area sources should be totally enclosed and equipped with access control systems. The potential effective dose equivalent should be evaluated for each installation.

Many facilities use a single radiation source contained in a shielded room with only one access point. Other facilities may use one radiation source for several rooms simultaneously. Concurrent area operation is common at accelerator installations where a beam can be deflected into one of several experimental areas. Access to one area may be required while a beam is being delivered to an adjacent area. In some

TABLE 6.1—*Radiation dose categories as a function of potential effective dose equivalent*

Potential Effective Dose Equivalent[a]		
rem	mSv	Dose Category
≤0.1	≤1.0	Minimum
>0.1 to 5	>1 to 50	Moderate
>5 to 25	>50 to 250	High
>25 to 100	>250 to 1000	Very high
>100	>1000	Extreme

[a] Determined using the protocol specified by Publication 26 (ICRP, 1977) and Report No. 84 (NCRP, 1985). Applies to whole body, partial body, or internal exposures.

cases, designing each area for the maximum output may not be practical. For example, one area may be designed to accept a small fraction of the total output while an adjacent area may be designed for the full output. Precautions must be taken to prevent the high output beam from entering the area shielded for a smaller output.

The processing of significant quantities of radionuclides normally takes place in fume hoods, glove boxes, or hot cells. Access to hoods and glove boxes is limited to hands and arms during normal use. Some glove boxes, however, may be large enough for a person to climb inside. Entry into these areas would be an unusual condition. Hot cells, where whole body exposure is more likely, may require access controls and alarm systems to activate or shut down ventilation systems if radioactivity has escaped from the confined area. Fuel reprocessing plants, where extremely large quantities of many different nuclides are separated at various stages of the process, require access control systems and alarm systems connected to ventilation systems and process controllers.

6.2 Access Control and Alarm Systems as a Function of Potential Dose

Access control and alarm systems should be selected on the basis of the potential dose to personnel from the radiation source or the potential levels of airborne radioactive material. The potential effective dose equivalent (or potential committed effective dose equivalent) is assigned a dose category ranging from minimum to extreme. The dose categories are listed in Table 6.1. Dose equivalents less than 100 mrem (1 mSv) are considered small and present a minor personnel hazard. Dose equivalents greater than 100 rem (1000 mSv) present an extreme hazard and can result in serious injury to the exposed individual. Intermediate dose equivalents from 5 rem to 25 rem (50 mSv to 250 mSv) present a lower risk; therefore less complex access-control and alarm systems can be used.

In selecting the dose category, the potential dose equivalent rate, the portion of the body exposed, and exposure time are used to arrive at a potential effective dose equivalent. By using Table 6.1, the appropriate dose category can be selected, and the recommended types of access control and alarm systems can be chosen from Table 6.2.

For example, calibration sources that produce 100 mrem/h (1 mSv/h) at 1 m would not require an alarm system. Ropes and signs would

TABLE 6.2—*Alarm and access control systems as a function of dose category*

Dose Category	Alarm System	Access Control Systems	Functional Logic
Minimum	None	Signs/Ropes	None
Moderate	Visual Audible	Signs Barriers[a]	None
High	Visual Audible	Interlocks Barriers[a], Signs	Maybe
Very High	Visual Audible	Interlocks Barriers[a] Signs/Lights/Audible	Yes
Extreme	Visual Audible	Interlocks Barriers[a] Signs/Lights/Audible Run/Safe and Emergency Off Switches	Yes

[a] Barriers in these dose categories normally include shielding materials such as concrete, steel, earth, and lead to reduce the radiation levels in occupied areas to acceptable levels.

normally provide adequate access control. Medical accelerators, on the other hand, can produce rates of 400 rem/min (4 Sv/min) in the beam and would require access control systems with functional logic to allow easy access for patient needs.

The same procedure can be used to select access control and alarm systems for facilities processing radioactive materials. In addition to the potential for external exposure, the potential internal exposure can be evaluated based on an assumed exposure scenario using Publication 26 (ICRP, 1977) weighting factors to arrive at a potential committed effective dose equivalent. The dose categories in Table 6.1 can be used to select the appropriate alarm and access control devices.

The access control and warning system recommendations in Table 6.2 are intended to serve only as guidelines. The actual access control and warning systems selected for a particular installation, particularly in the high-to-extreme dose categories, should be specified and designed by qualified engineers and health physicists.

7. Education and Training

Education and training play an important role in radiation safety. They have importance in connection with alarm and access control systems because it is essential that personnel understand the various concepts, systems and devices utilized.

NCRP Report No. 71 (NCRP, 1983), "Operational Radiation Safety Training," provides guidance for conducting an effective operational radiation safety training program. On the basis of a thorough evaluation of the physical facility and the processes to be conducted there, the degree and nature of potential radiation exposures can be identified. Information in Report No. 71 can then be used for developing an effective facility training program.

Prior to the assignment of any person to a position in a radiation facility, management should first determine that the person has received the necessary formal education or demonstrated equivalent proficiency to qualify that person for the specific job assignment. This formal education requirement is normally fulfilled before a person is employed. However, there are situations where in-house promotions may result from individual off-the-job formal education achievements or formal education courses provided by facility management.

It is management's responsibility to ensure that an effective training program is being carried out for all personnel who work in or may enter the facility. Facility management should: (1) develop a well defined policy on radiation safety and radiation safety training and make it routinely known to all facility personnel; (2) establish a staff of qualified training personnel (or make suitable arrangements with a consulting organization) and support the training staff with necessary training facilities and training resources; (3) provide for independent auditing of the training program to ensure that it is effective and that all administrative and regulatory requirements are being complied with; and (4) establish an administrative program to be followed should disciplinary action be required for personnel not complying with the safety program requirements.

The training program should emphasize the objective of keeping personnel radiation exposures as low as reasonably achievable. The program should include a session on the employee's responsibilities for maintaining personnel radiation exposure at the lowest possible level. The program must emphasize that facility personnel are a key element in the effective operation of the alarm and access control systems and that these systems are not to be routinely bypassed to operate the facility. Emphasis should also be placed on the need for all facility personnel to be constantly alert to the status of facility alarm and access control systems.

All personnel who occupy the facility routinely must be provided training specific to the hazards associated with those areas of the facility where they work and to their job assignments. As a minimum, they must know: (1) the basic facility radiation safety program, including the details of the access control system; (2) the potential hazards and associated health risks that can be encountered; (3) the meaning of instructional signs and activated alarm devices; and (4) the action they are to take when alarm devices are activated. In addition to these basic training requirements, certain personnel should receive specialized training as specified in the following paragraphs.

Operating personnel should be trained to: (1) operate the facility properly; (2) know what radiation monitoring and nonradiation monitoring instrumentation is present to alert personnel to the operating status of the facility; and (3) know what the operating equipment and safety system logic systems will do in case abnormal operations are encountered in the facility. They should know the location and levels of hazardous radiation that exist and the health significance should personnel be exposed to them. All operating personnel should be trained in all these aspects and should be supervised by experienced employees until such time as they have demonstrated operating competence and the necessary level of knowledge of the facility operating parameters. Formalized testing and documentation of training and testing are recommended to demonstrate proper assimilation of the training information.

Maintenance personnel should be trained in the detailed maintenance aspects of the facility equipment. It is important that these personnel be trained in the specific instrumentation and controls for the facility in which they work. ISA Standard ISA-67.14 (ISA, 1983) provides detailed information on the training requirements for these personnel.

Contract personnel assigned to work in a radiation facility should be provided with at least the minimum training specified above. In addition, they should be provided information and training in the specific tasks they are to perform and the radiation hazards they may encounter in those tasks. Less training may be required if they are under the constant supervision of trained facility personnel.

Emergency response personnel need to be provided training so that they will be able to respond properly in case of a facility emergency such as a fire, a large radiation source stuck in an unshielded position, a power outage, or a facility evacuation alarm. Routine tours of the facility should be provided to ensure that they remain familiar with the physical features and arrangement of the facility and the location of emergency equipment. Routine refresher training should be conducted to ensure that they remain familiar with emergency procedures and equipment.

Casual visitors to the facility need not be given extensive training if they are accompanied by trained facility personnel while in the facility. Visitors who may be performing work within the facility should be trained as if they were permanent facility employees, giving due consideration to length of work schedule, radiation exposure potential, and amount of supervision to be provided by facility personnel.

In facilities where emergency evacuations may be required, routine drills should be performed at least annually to ensure that all personnel are familiar with the emergency procedures. An appropriate announcement should be made prior to activating the emergency systems to ensure that personnel understand that only a drill is being performed.

A retraining program should be conducted on a regular basis to ensure that facility personnel remain familiar with all aspects of the radiation safety program and are kept current on facility operating parameters and procedures.

Appendix A:

Discussion of Reliability

One of the main techniques used to enhance the reliability of radiation alarm and access control systems is the selection of fail-safe components. In addition, redundant components are often used to enhance reliability. The most extensive use of redundancy has been in the aerospace and nuclear energy fields to increase the reliability of complex equipment.

The fundamental assumption underlying the use of redundancy to increase reliability of nonabsolute fail-safe devices is that any such device or process can malfunction or go out of adjustment. Thus, a backup device or system is frequently provided to take over the operation in case the primary one fails. However, there may be no signal that an error has occurred or that the sensitivity of an instrument has shifted. To reduce the chance of undetected errors or instrument drift, one redundantly compares independent items even though no problem is apparent.

In order to determine quantitatively the reliability of a redundant system, it is necessary to determine the reliability of the individual components.[1] For a wide range of devices and instruments, it has been found that the reliability, or the probability that no failure will occur in time t, is approximately $\mathrm{R} = \exp(-t/T)$, where T is the mean time between failures. This formula is based on the assumption of a constant failure rate with time. The probability of a failure occurring in time t is then $\mathrm{p} = 1 - \exp(-t/T)$, which approaches t/T for small values of t/T. There are several justifications for the use of the assumption of a constant failure rate. It has been found to agree with the observed failure rate of some electronic equipment, and it yields a probability based on a single parameter that is easy to comprehend. In statistical terms, the probability that two or more independent safety devices will fail in a given time period is simply the product of the individual probabilities. If a device has a failure rate which is not constant, *e.g.*, higher after it is first installed, the following example calculation would not be applicable.

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[1] The formulae presented are based on the assumption that the redundant components are in parallel. Procedures do exist for calculating the reliability of more complex systems where redundancy is applied in a combination of series and parallel components (Bergman, 1985; Lynott, 1982). The formulation used here also assumes that all the components that are redundantly compared are independent.

One of the items in an access control system that requires periodic testing is the door interlock. As an example, the estimated probability of an accident occurring as a result of an individual entering a high-radiation area after the door interlock has failed can be calculated as follows. It is assumed that the interlock is never left in a bypassed condition even though this has occurred in several documented accidents. It is further assumed in this example that the mean time between short circuits of the door interlock is 100 years. The mean time between inadvertent entry into these areas while the radiation is "on," bringing the interlock into play, will be assumed to be 10 years. The probability of inadvertent entry into a high-radiation area following an interlock failure is a function of the frequency of checking on the operation of the door interlock. Then with yearly checks on the interlocks, the probability per year of entry when the interlock has failed is

$$\frac{1}{10} \times \frac{t}{T} = \frac{1}{10} \times \frac{1}{100} = 10^{-3}.$$

If the interlock is checked each month then the probability of an accident per year is

$$\frac{1}{10} \times \frac{1/12}{100} = 8 \times 10^{-5},$$

which is 1/12th that of yearly checking. That is, the probability will decrease linearly with the increase in frequency of checking.

Now consider two independent interlocks, each with a mean time between failures of 100 years. Then, with yearly checking, the probability of an accident per year is

$$\frac{1}{10} \times \frac{1}{100} \times \frac{1}{100} = 1 \times 10^{-5},$$

and with monthly checking it is

$$\frac{1}{10} \times \frac{1/12}{100} \times \frac{1/12}{100} = 7 \times 10^{-8},$$

or 144 times less than with annual checking. Thus, the probability of an accident per year is 1,200 times less with two independent interlocks checked monthly than with one interlock checked monthly.

Information on the failure rates for various electromechanical components that could be used in access control and alarm systems can be found in the Electronic Engineer's Master Catalog (Spector, 1984).

Appendix B:

Examples of Access Control and Alarm Systems

The following are brief descriptions of typical access control and alarm systems. They are intended to serve as examples only. There is no intent to imply that they are more acceptable than other suitable systems.

B.1 Neutron Criticality Alarm System

The neutron criticality alarm system shown in Figure B.1 is based on a design originally developed by Friend and modified by Zuerner and Weddle (Friend, 1966; Zuerner and Weddle, 1972). The system uses the amplified output from a polyethylene moderated BF_3 tube to drive a one-shot multivibrator that, in turn, activates an alarm through a redundant trip circuit. The alarm circuits are basically voltage sensitive counting rate devices using an integrating capacitor that fires a unijunction transistor when the counting rate equals or exceeds the alarm set point. The unijunction, in turn, fires a silicon-controlled rectifier to activate the alarm relays. The backup alarm circuit is set

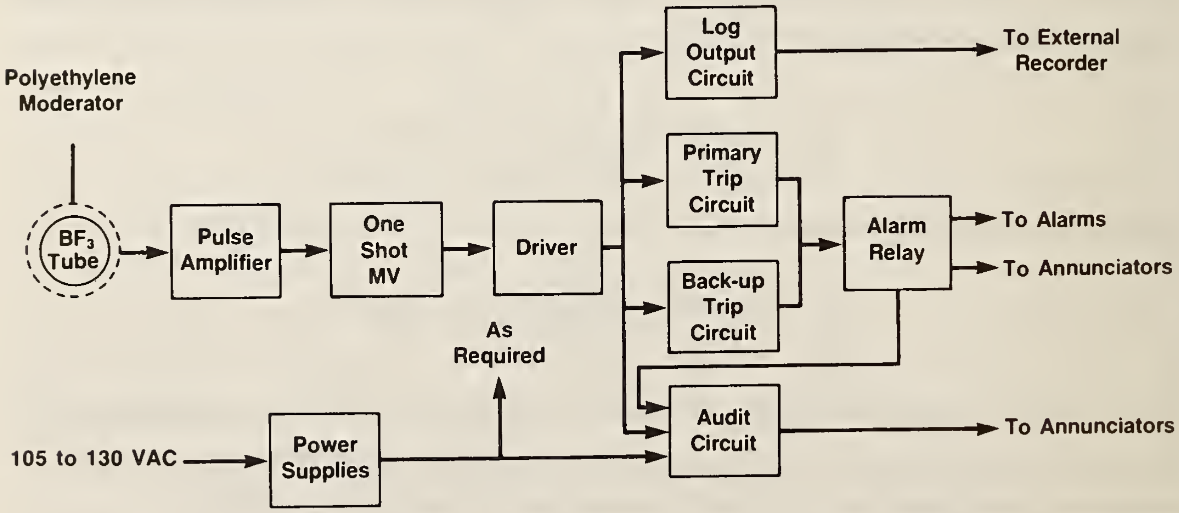

Fig. B.1. Neutron Criticality Alarm System (only one detector and associated circuitry are shown)

to fire at a slightly higher counting rate than the primary alarm circuit, but either circuit will drive the alarm.

An important feature of the system is an audit circuit that checks the operation of the detector by determining its response to the background neutron fluence rate from cosmic rays. If a signal is not received from the detector in a given time period, or if the AC-line voltage has dropped below the value for proper operation, a failure signal is activated, and an external signal is also provided.

The individual detector systems are used in a two out of "n" system to minimize false alarms from malfunction of a single detector. That is, it requires two separate detectors out of "n" total detectors to activate the alarm. Two equal detection circuits are used in parallel and form a comparator network using diode logic.

B.2 Area Radiation Alarm System

Among the numerous designs for remote area radiation alarms is a relatively simple system using a differential voltage comparator circuit to control the alarm. This system obviates the problems associated with movable contact meter relays, including limitation on readout and poor relay reliability. An area monitoring system based on differential voltage comparator circuitry equipped with commercially available transistors has been successfully used at several locations, including the High Flux Beam Reactor at Brookhaven National Laboratory (Chester, 1972). The block diagram of this system is shown in Figure B.2.

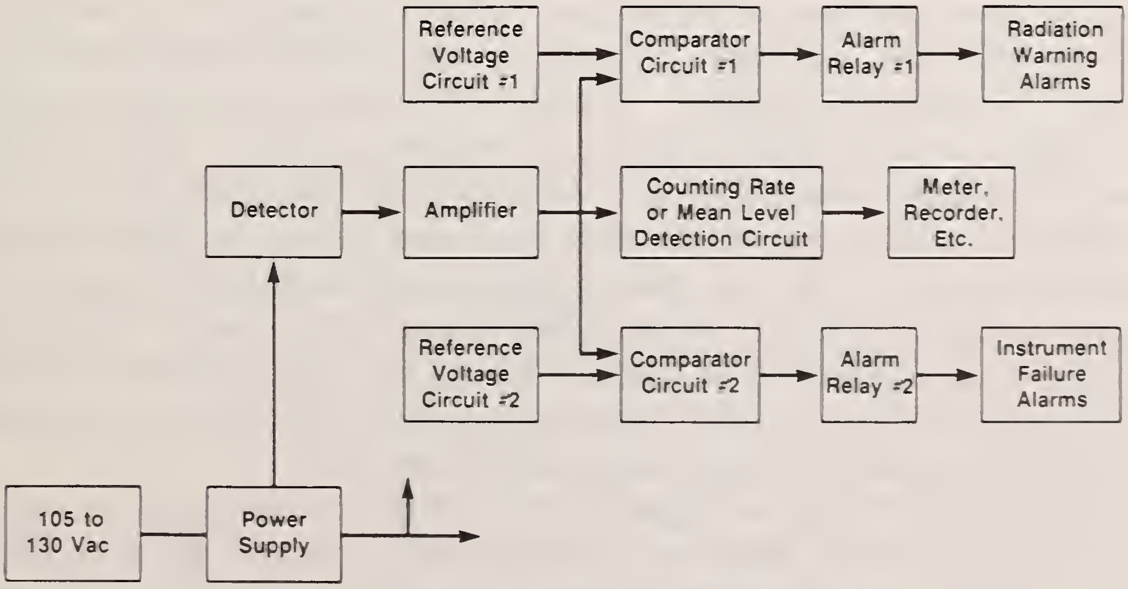

Fig. B.2. Voltage Comparator Warning Circuit.

A differential voltage comparator is a high-gain differential single-ended output amplifier that compares a signal voltage with an adjustable reference voltage that can be set to any desired level, and hence provides maximum flexibility of alarm level. When the signal voltage exceeds the reference voltage, a change in output level results, providing a signal that can be used to actuate the alarm. The actuation of the alarm does not interfere with measurement of the intensity of the radiation field obtained from a standard counting rate meter or mean level detection system.

Multiple alarm levels can be obtained by the use of several appropriately set comparator circuits; similarly, a comparator circuit can be used as a detector or instrument failure alarm by comparing the reference voltage with the input signal from background radiation. If no input signal is received from the detector, the output of the comparator will drop to zero, allowing a relay to open and activate the failure warning system. If background levels are insufficient for comparison purposes, a small source can be used to provide a suitable signal from the detector.

B.3 Access Control System for an X-Ray Machine

A typical design of an access control system for an x-ray machine is shown in Figure B.3 (Victor, 1979). The access control system incorporates interlocks; warning lights indicating the status of power to the unit, when x-rays are being produced, and the position of the shutter; meters displaying current and voltage readings; a key switch; a timer; and an emergency off button.

The x-ray machine is turned on, and x-ray production is initiated by the following sequence of events: First, the line control switch is closed. This provides power to the filament control circuit, the “power on” light, the timer switch, and door interlock contacts. Next, the key switch to high voltage supply is activated. At this point, if the door interlock switches are closed and the timer switch is closed (timer activated), the “x ray on” button is pushed. Closing the “x ray on” switch activates coil K1 which closes contacts K1-1 and K1-2, which allows x-ray production to begin. Closing the “open shutter” switch activates the solenoid which opens the shutter. This, in turn, activates coil K4, the shutter “open” light, and contact K4-1.

If either the “x-ray on” light or the external warning device burns out, coil K2 or K3 drops out, opening either contact K2-1 or K3-1 and halting x-ray production. Also, if the shutter “open” light burns out, coil K4 drops out, causing the shutter to be closed.

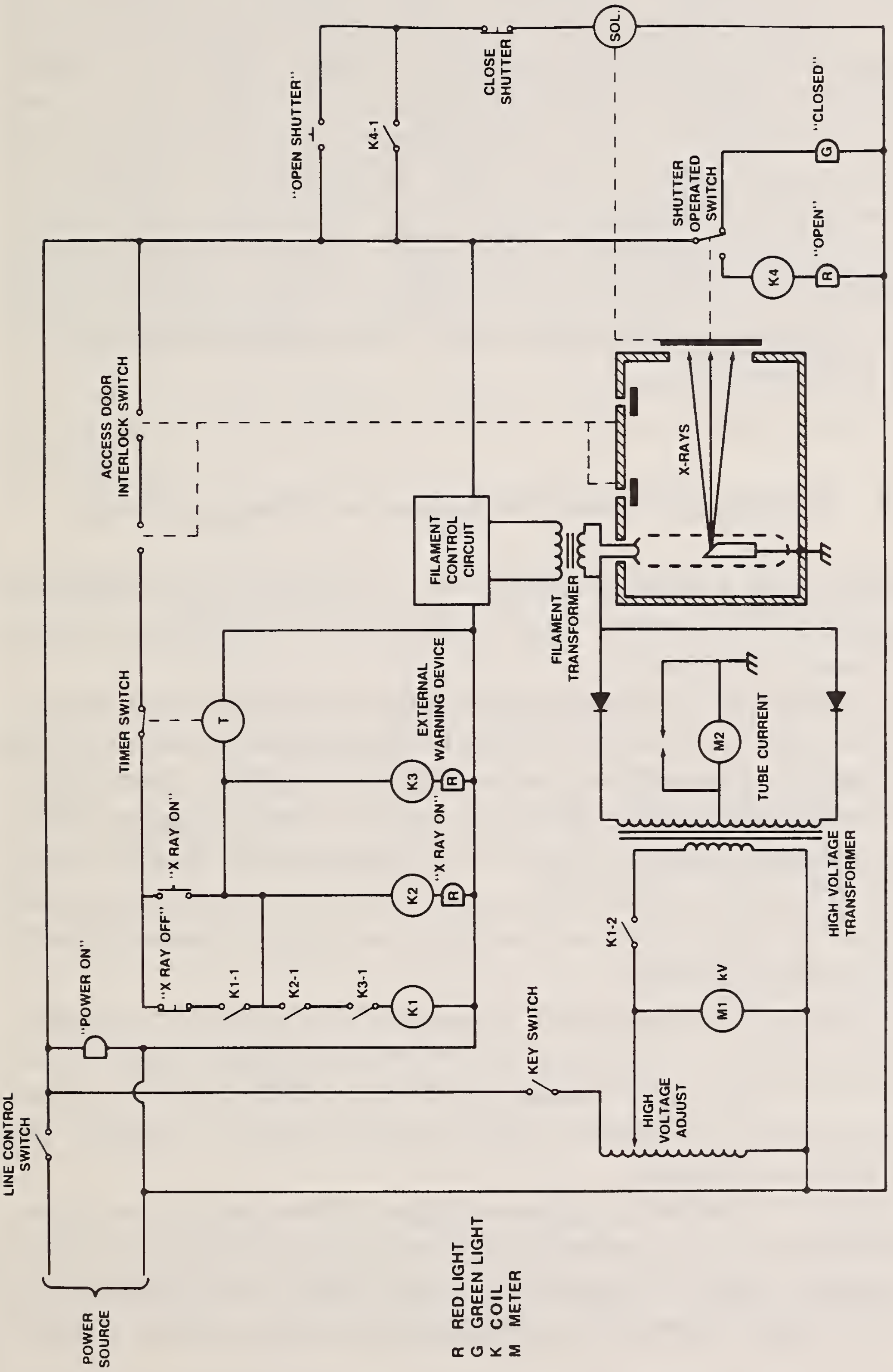

Fig. B.3. Typical X-Ray Machine with Associated Access Control System

However, failures can still occur that could result in a hazardous condition. For example, if the high-voltage contact K1-2 fails, x rays could be produced whenever power is supplied to the x-ray machine. Also it is possible that the high-voltage and tube-current meters could fail or that the timer or interlock contacts could fail in the closed position. In an attempt to alert the operator to these potential malfunctions, an x-ray safety box has been developed at Lawrence Livermore National Laboratory (Victor, 1979). Its function is to monitor the interlock circuits, the high-voltage control circuit, the high-voltage contactor, and the warning lamps or indicators. If the x-ray safety box detects any abnormal conditions in any of the critical components, it shuts the machine down.

B.4 Revolving Cobalt-60 Radiation Therapy Unit

The following is a brief discussion of the factors to be considered when establishing an access control system at a radiation therapy facility (Lanzl *et al.*, 1955).

When a patient is undergoing radiation treatment for cancer, typically no other person is, or should be, in the treatment room. Access to the treatment room is almost universally provided by a single entry, which is controlled by a door. From the point of view of patient safety, it is recommended that the door not be mechanically locked during treatment. When the unit is not in use, however, it is recommended that the door be kept locked so that the possibility of tampering with the therapy unit is reduced.

The door should be equipped with an interlock. If the door is opened, either intentionally or inadvertently, the beam shutter is closed or the source is returned to a safe shielded position. In addition, if the system is revolving around the patient, when the access door is opened, the revolving motion will stop.

Access is also controlled by lights and signs. When the source shutter is in the closed position, a green light is turned on; in the open position, a red or magenta light is turned on. A set of lights is normally located on the control panel, above the entrance door, and on the teletherapy head.

When the source shutter is opened, a reasonably constant level of scattered radiation is present at locations near the axis of revolution of the source shield, especially when a patient is present in the primary beam. As part of the alarm system, a radiation monitor is mounted on a wall near the axis of revolution of the source shield. The monitor is intended to detect scattered radiation only, and therefore it should not intersect the primary beam of radiation regardless of the orientation of the shield and the setting of the beam collimators.

With the shutter closed, the scattered-radiation level at the monitor is essentially zero. When the shutter is open, the monitor signal will vary depending on the beam direction, field size, and location of objects in the beam. The monitor signal should trigger a dual-level alarm (horn) system. The lower level alarm functions if the door is opened while the shutter is open. Typically, the door interlock automatically causes the shutter to close, but the horn will sound briefly because of the time lag in the shutter closing. The higher level triggers the alarm with the door either open or closed if the dose rate exceeds the dose rate expected from scattered radiation. This would indicate a source dislocation.

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2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units, and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations;
3. Develop basic concepts about radiation quantities, units, and measurements, about the application of these concepts, and about radiation protection;
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units, and measurements and with radiation protection.

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  - Task Group 6 on Radiation Protection for Allied Health Personnel
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  - Task Group 9 on Lung Cancer Risk
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American Radium Society
American Roentgen Ray Society
American Society of Radiologic Technologists
American Society for Therapeutic Radiology and Oncology
Association of University Radiologists
Atomic Industrial Forum
Bioelectromagnetics Society
College of American Pathologists
Conference on Radiation Control Program Directors
Federal Communications Commission
Federal Emergency Management Agency
Genetics Society of America
Health Physics Society
National Bureau of Standards
National Electrical Manufacturers Association
Radiation Research Society
Radiological Society of North America
Society of Nuclear Medicine
United States Air Force
United States Army
United States Department of Energy
United States Department of Housing and Urban Development
United States Department of Labor
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Service

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the special liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the special liaison program:

Commission of the European Communities
Commisariat a l'Energie Atomique (France)

Defense Nuclear Agency
Federal Emergency Management Agency
Japan Radiation Council
National Bureau of Standards
National Radiological Protection Board (United Kingdom)
National Research Council (Canada)
Office of Science and Technology Policy
Office of Technology Assessment
United States Air Force
United States Army
United States Coast Guard
United States Department of Energy
United States Department of Health and Human Services
United States Department of Labor
United States Department of Transportation
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission

The NCRP values highly the participation of these organizations in the liaison program.

The Council's activities are made possible by the voluntary contribution of time and effort by its members and participants and the generous support of the following organizations:

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The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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2	*Quantitative Risk in Standards Setting*, Proceedings of the Sixteenth Annual Meeting, Held on April 2–3, 1980 (Including Taylor Lecture No. 4) (1981)
3	*Critical Issues in Setting Radiation Dose Limits*, Proceedings of the Seventeenth Annual Meeting, Held on April 8–9, 1981 (Including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Procedures*, Proceedings of the Eighteenth Annual Meeting, Held on April 6–7, 1982 (Including Taylor Lecture No. 6) (1983)
5	*Environmental Radioactivity*, Proceedings of the Nineteenth Annual Meeting, Held on April 6–7, 1983 (Including Taylor Lecture No. 7) (1984)
6	*Some Issues Important in Developing Basic Radiation Protection Recommendations*, Proceedings of the Twentieth Annual Meeting, Held on April 4–5, 1984 (Including Taylor Lecture No. 8) (1985)
7	*Radioactive Waste*, Proceedings of the Twenty-First Annual Meeting, Held on April 3–4, 1985 (Including Taylor Lecture No. 9) (1986)

Symposium Proceedings

The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack, Proceedings of a Symposium held April 27–29, 1981 (1982)

Lauriston S. Taylor Lectures

No.	Title and Author
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)
2	*Why be Quantitative About Radiation Risk Estimates*? by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk*, see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980) [Available also in *Quantitative Risks in Standards Setting*, see above]
5	*How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits*, see above]
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7	*The Human Environment-Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above]
8	*Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]
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2	*Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982)
3	*Screening Techniques for Determining Compliance with Environmental Standards* (1986)

NCRP Reports

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9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951)
16	*Radioactive Waste Disposal in the Ocean* (1954)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons and Mixtures of Neutrons and Gamma Rays* (1961)
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1	*X-Ray Protection* (1931). [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934). [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936). [Superseded by NCRP Report No. 6]
4	*Radium Protection* (1938). [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compounds* (1941). [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949). [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949). [Superseded by NCRP Report No. 30]
10	*Radiological Monitoring Methods and Instruments* (1952). [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953). [Superseded by NCRP Report No. 22]
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13	*Protection Against Radiations from Radium, Cobalt-60 and*

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18	*X-Ray Protection* (1955). [Superseded by NCRP Report No. 26]
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31	*Shielding for High Energy Electron Accelerator Installations* (1964). [Superseded by NCRP Report No. 51]
34	*Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation* (1970). [Superseded by NCRP Report No. 49]

Other Documents

The following documents of the NCRP were published outside of the NCRP Reports series:

"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology 63, 428 (1954)

"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. 84, 152 (1960) and Radiology 75, 122 (1960)

X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements (National Council on Radiation Protection and Measurements, Washington, 1968)

Specification of Units of Natural Uranium and Natural Thorium (National Council on Radiation Protection and Measurements, Washington, 1973)

NCRP Statement on Dose Limit for Neutrons (National Council on Radiation Protection and Measurements, Washington, 1980)

Control of Air Emissions of Radionuclides (National Council on Radiation Protection and Measurements, Bethesda, Maryland, 1984)

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